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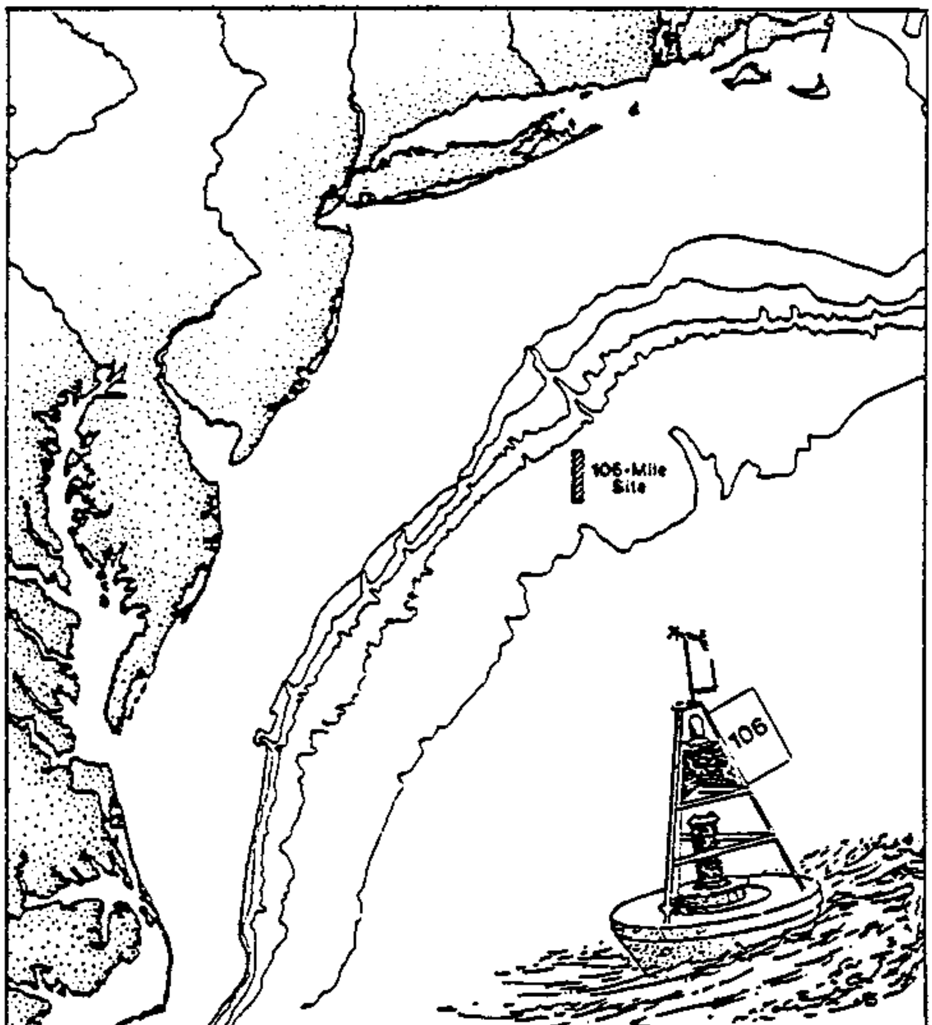
Determination of Sludge Dumping Rates for the 106-Mile Site



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FINAL REPORT

DETERMINATION OF SLUDGE DUMPING RATES FOR THE 106-MILE SITE

March 15, 1989

U.S. ENVIRONMENTAL PROTECTION AGENCY
Region II
New York, New York
and
Office of Marine and Estuarine Protection
Washington, DC

Prepared Under Contract No. 68-03-3319

FINAL REPORT

DETERMINATION OF SLUDGE DUMPING RATES FOR THE 106 MILE SITE

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U.S. ENVIRONMENTAL PROTECTION AGENCY

Region II
New York, New York

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Office of Wetlands, Oceans
and Watersheds
Washington, D.C.

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EXECUTIVE SUMMARY

The U.S. Environmental Protection Agency (EPA), under the Marine Protection, Research, and Sanctuaries Act of 1972, is responsible for regulating the disposal of sludge at the 106-Mile Deepwater Municipal Sludge Site (106-Mile Site) located approximately 100 nmi offshore New York and New Jersey. EPA has developed a monitoring plan (EPA , 1992a) for the 106-Mile Site which ensures that regulatory requirements are met, and that field measurements are made to support site management decisions. As part of the monitoring plan, a series of field measurement surveys has been conducted to monitor the nearfield behavior and fate of sludge dumped at the 106-Mile Site. These measurements represent a high-quality data set from which to base analyses of nearfield, short-term sludge plume dilution and compliance with marine water quality criteria.

EPA received sludge dumping permit applications for continued use of the 106-Mile Site from nine sewerage authorities in New York and New Jersey, and is in the process of reviewing the applications to determine whether the proposed dumping operations will comply with water quality criteria. As part of this review process, EPA must determine whether the court-ordered dumping rate of 15,500 gal/min is suitable for the 106-Mile Site, or whether dumping rates and strategies must be altered. This report presents analyses that will aid EPA in making sound management decisions concerning the dumping of sewage sludge at the 106-Mile Site. The study focuses on three major objectives:

- Development of an empirical equation for calculating optimum sludge dumping rates, based upon field observations of sludge plume behavior at the 106-Mile Site.
- Calculation of sludge dumping rates for individual permit applicants, based upon sludge characteristics.
- Development of candidate strategies for multiple dumping at the 106-Mile Site.

The following activities were conducted as secondary objectives:

- An assessment of whether the existing models of waste plume dilution are suitable for prediction of sludge plume dispersion at the 106-Mile Site.

- A preliminary survey of the physical characteristics and dumping procedures for the barges that dump sludge at the 106-Mile Site.

Analyses of the physical and chemical measurements obtained during the nearfield monitoring surveys in September 1987 and 1988 indicate that sludge plumes are not dispersed rapidly during summer conditions; plumes are generally confined to the upper 25 m of the water column during the first 4 h after dumping. Dilutions of sludge parcels within the core of the plumes were on the order of 4,000:1 4 h after dumping at rates between 12,000 and 15,000 gal/min.

Analyses of trace metals and toxicity data provided in the dumping permit applications and obtained from analyses of whole sludge samples obtained in August 1988 indicate that sludge dilutions at 4 h must be much greater than 10,000:1 for many of the sewerage authorities. These dilution requirements are based upon compliance with specific water quality criteria for metals and toxicity 4 h after sludge is dumped. Metal-based and toxicity-based dilution requirements differ significantly for each sewerage authority, and large differences are observed among the nine authorities in New York and New Jersey. To achieve these high dilutions, sludge dumping rates must be reduced greatly because oceanic mixing processes, at least during summer, are not sufficient for attaining this degree of dilution over a period of 4 h; winter monitoring surveys will be necessary to determine whether oceanographic mixing processes are significantly more intense during winter.

An empirical equation has been developed for calculating the optimum sludge dumping rate for each permit applicant, based upon the field data from the September 1987 and 1988 monitoring surveys. The results indicate that dumping rates should be less than 1,000 gal/min for three of the permit applicants and less than 5,000 gal/min for the remaining six applicants to ensure compliance with water quality criteria 4 h after dumping. It is recommended that additional nearfield data be acquired during plume monitoring surveys in order to validate the coefficients in the empirical dumping rate formula: however, the results from the September 1987 and 1988 surveys are viewed as an excellent data set from which to base a conservative model of sludge plume dilution at the 106-Mile Site.

1. INTRODUCTION

The U.S. Environmental Protection Agency (EPA), under the Marine Protection, Research, and Sanctuaries Act of 1972 (MPRSA, PL 92-532) is responsible for regulating the disposal of municipal sewage sludge in ocean waters. As a result of an April 11, 1985, decision to deny petitions to redesignate the 12-Mile Sludge Site offshore New York, EPA Region II halted all sludge disposal in New York Bight. Effective January 1, 1988, all municipalities in the New York and New Jersey have shifted sewage sludge disposal operations to the 106-Mile Deepwater Municipal Sludge Site (106-Mile Site).

EPA has developed a monitoring plan (EPA , 1992a) for the 106-Mile Site which ensures that regulatory requirements are met, and that field measurements are made to support management decisions concerning (1) site redesignation or dedesignation, (2) issuance, continuation, or revocation of sludge dumping permits, and (3) continuation, modification, or termination of the monitoring program itself. The overall strategy of the monitoring plan, and its companion implementation plan (EPA , 1992b), focuses on two areas of concern: assessment of compliance with permit conditions and assessment of potential impacts of sludge disposal on resources and other aspects of the marine environment.

As part of the 106-Mile Site monitoring plan, EPA has conducted a series of field measurement surveys to monitor the nearfield behavior and fate of sewage sludge dumped at the 106-Mile Site (EPA , 1992c; 1988a; 1988b). These surveys (in September 1987 and March and September 1988) provided accurate, high-resolution measurements of physical and chemical properties within sludge plumes immediately after dumping. The physical measurements were used to determine the physical characteristics of the sludge plumes and the effects of oceanographic processes on sludge plume dilution and advection. The chemical measurements were used to determine rates of sludge dilution and to test compliance with marine water quality criteria.

EPA received dumping permit applications for continued use of the 106-Mile Site from nine sewerage authorities in New York and New Jersey, and is in the process of reviewing the applications to determine whether the proposed sludge dumping operations will comply with marine water quality criteria. As part of this review process, EPA must determine whether the court-mandated sludge dumping rate of 15,500 gal/min is suitable for the 106-Mile Site, or whether dumping rates and strategies must be altered to ensure compliance with water quality criteria (WQC) and toxicity-based limiting permissible concentrations (LPCs). These management decisions will require analyses of monitoring studies followed by regulatory decisions as illustrated in Figure 1.1; the four major components of this regulation/monitoring scheme are described below.

- **Regulation**, whereby sludge dumping rates are established and routinely monitored for compliance with water quality criteria.
- **Dumping Operations**, wherein the effective rate of sludge disposal is based upon volume dumping rates and barge speed.
- **Sludge Dispersion**, which is governed by dumping rates, barge characteristics, and oceanographic dispersion processes.
- **Monitoring**, whereby field measurements and water samples are used to test compliance with water quality criteria and recommend changes to, or maintenance of, sludge dumping rates.

Work Assignment 1-111 of Contract No. 68-03-3319 was initiated to provide EPA with technical assistance on various operational aspects of the 106-Mile Site sludge dumping program, including the evaluation of appropriate sludge dumping rates. This report presents the results of Task 1 of Work Assignment 1-111. The major objectives of this task include

- An assessment of whether the existing models of waste plume dilution are suitable for prediction of sludge plume dispersion at the 106-Mile Site.
- A survey of physical characteristics and dumping procedures for the barges that dump sludge at the 106-Mile Site.
- Development of an empirical formula for calculating optimum sludge dumping rates, based upon field measurements of sludge plumes at the 106-Mile Site.
- Calculation of sludge dumping rates for individual permit applicants, based upon sludge characteristics.
- Development of candidate strategies for multiple dumping at the 106-Mile Site.

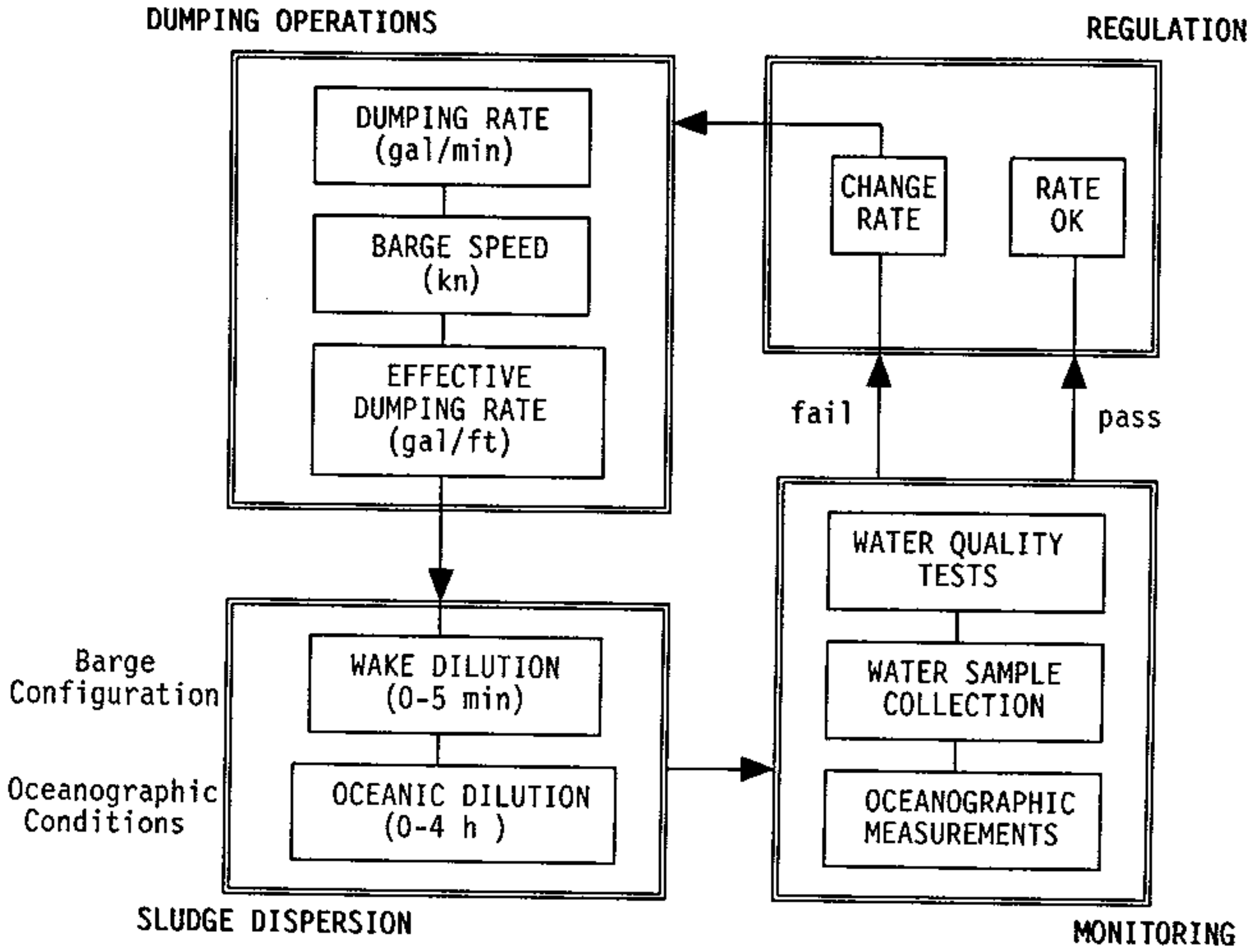

FIGURE 1.1 SCHEMATIC DIAGRAM OF ACTIVITIES ASSOCIATED WITH THE REGULATION AND MONITORING OF SLUDGE DUMPING RATES FOR THE 106-MILE SITE.

This report is structured in sections that address the specific objectives given above. Section 2 presents information on existing models of waste plume dilution, barge characteristics, and field observations of sludge plume behavior at the 106-Mile Site. The derivation of an empirical formula for calculating optimum sludge dumping rates is given in Section 3. Section 4 presents recommended dumping rates for individual permit applicants, in addition to a nomograph for quick determination of optimum dumping rates for a wide variety of sludge dilutions in receiving water. Section 5 presents a number of operational strategies for dumping sludge at the 106-Mile Site. Recommendations for additional analyses and field studies are given in Section 6. References are listed in Section 7.

2. BACKGROUND INFORMATION

This section presents background information on three topics that pertain to ocean disposal of sewage sludge. Subsection 2.1 provides a brief review of existing models of waste plume dispersion; rationale is given for the use of field data over existing models when estimating sludge dilution. Subsection 2.2 describes the physical dimensions, sludge capacity, and dumping procedures of the barges that transport sludge to the 106-Mile Site. Field observations of sludge plume dilution from a recent EPA cruise to the 106-Mile Site are discussed in Subsection 2.3.

2.1 REVIEW OF EXISTING DILUTION MODELS

The ocean dumping regulations require calculation of the limiting permissible concentration (LPC) for wastes that are to be dumped in the ocean. The LPC is the concentration of a constituent, after allowance for initial mixing, that does not exceed (1) applicable marine WQC and (2) a toxicity threshold, defined as 0.01 of a concentration shown to be acutely toxic to appropriate, sensitive marine organisms. The LPC is used to calculate the maximum allowable dumping rate based on the initial mixing of the waste. Initial mixing is defined as the mixing that occurs within 4 hours of dumping.

The ocean dumping regulations allow for several methods of calculating initial mixing. These methods, in order of preference, are as follows:

1. When field data on the proposed dumping activities are adequate for prediction of initial dispersion and dilution of the waste, these data shall be used. If necessary, the field data should be used in conjunction with an appropriate mathematical model of waste mixing and dilution.

2. When field data on the dispersion and dilution of a waste similar in characteristics to that proposed for discharge are available, these data shall be used in conjunction with an appropriate mathematical model.

3. When no field data are available, theoretical oceanic turbulent diffusion relationships may be applied to known characteristics of the waste and the disposal site.

4. When no other means of estimation are feasible, a procedure for calculating initial mixing is presented in the regulations.

The regulations thus emphasize that when field data are available, these data should be used in the estimation of initial mixing. As a result of the recent nearfield monitoring studies at the 106-Mile Site (EPA , 1992c; 1988a; 1988b), high-quality field data are now available for estimating the initial mixing of sludge dumped at the 106-Mile Site. The question that remains is what model, if any, should be used with these data to estimate the amount of initial mixing, and hence, the optimum rate for dumping sludge at the 106-Mile Site.

Because the regulations state that the procedure for calculating initial mixing which is specified in Part 227 of the Code of Federal Regulations (CFR) should be used only "when no other means of estimation are feasible," this "model" is not appropriate for estimating the initial mixing of sewage sludge dumped at the 106-Mile Site.

Since the mid-1970s, ten "state of-the-art" models have been used to predict initial mixing of dumped wastes (see Table 2.1). These models have been reviewed (EPA , 1986) to determine the extent to which they had been validated with field data, and to ascertain the types of materials for which they are appropriate. The following statements are based upon the above-mentioned review of mixing models.

Of all the models presented in Table 2.1, none are presently capable of predicting maximum concentrations of isolated parcels of sludge in ocean water. These models predict either average or Gaussian-distributed concentrations of disposed material in receiving waters. With the exception of the Walker et al. (1987) sewage sludge model and the Offshore Operators Committee (OOC) Mud Discharge Model (Brandsma et al., 1983), all of the models are inappropriate for, or would require major revisions before use in, estimating initial mixing of sewage sludge in oceanic waters.

The Walker et al. model was developed specifically for analyses of sewage sludge disposal at the 106-Mile Site. Its major application is predicting farfield dispersion characteristics of sewage sludge. The model predicts average, steady-state concentrations of sludge constituents over the farfield, but the results are based upon an empirical algorithm (with inherent, non-conservative assumptions) rather than a deterministic solution.

TABLE 2.1 ASSESSMENT OF MODELS FOR PREDICTION OF INITIAL MIXING OF SLUDGE DUMPED AT THE 106-MILE SITE.

Authors	Year	Material	Validation	Appropriate for Initial Mixing
Brandsma and Divoky	1976	Dredged material	Field and lab	No
Brandsma, Sauer, and Ayers	1983[a]	Drilling muds and produced water	Field and lab	Potentially
Christodoulou et al.	1974	Suspended sediments	Some	No
Economic Analysis and ASA	1986	Spilled oil	None	No
Goldenblatt and Bowers	1978	Dredged material	Lab	No
Koh and Chang	1973	Dredged material	Field and lab	No
Krishnappen	1983	Dredged material	Lab and other models	No
Lavelle et al.	1981	Suspended sediments	Field	No
Walker, Paul, and Bierman	1987	Sewage sludge	None	Doubtful
Wu and Leung	1983	Drilling muds	Other models	No

[a]Final versions of produced water and drilling mud models will be available in February 1989. The drilling mud model was field validated for the important convective descent phase (O'Reilly et.al, 1988), and laboratory validated for convective descent and dynamic collapse phases (Brandsma and Sauer, 1983).

Although the model cannot be validated by field measurements, the general concensus is that it overestimates long-term dilutions.

The OOC Mud Discharge Model, which is being expanded to include fluids without particles, can predict the nearfield and farfield dispersion of almost any type of discharged fluid, including sewage sludge, for most current regimes. The model contains the appropriate phases of dispersion dynamics to predict dilution of dumped material; convective descent, dynamic collapse, and passive diffusion. The first two phases that are important to initial mixing have been laboratory and field validated for drilling fluid discharges. Although this model only considers discharges from a fixed point, it can easily be modified to predict dilutions from a moving barge. It also has the capability to consider wake effects and particle flocculation.

Presently, the computer models that are available for use in modeling dispersion and initial mixing of sewage sludge dumped in the 106-Mile Site are inapplicable. There are, however, candidate models as noted above that have the potential of being used for sewage sludge dispersion determinations after modification and/or verification. At this time, the recent nearfield monitoring surveys at the 106-Mile Site provide the best alternative for evaluating initial mixing.

2.2 CHARACTERIZATION OF SLUDGE TRANSPORT BARGES

This subsection presents a preliminary survey of the characteristics of barges that are used to transport sewage sludge from New York and New Jersey to the 106-Mile Site. Information on these barges was obtained from files maintained by EPA Region II, and by contacting the New York City Department of Environmental Protection and the various transportation companies identified below.

2.2.1 Barge Characteristics

Sludge transport vessels are operated by the New York City Department of Environmental Protection (NYCDEP) and four private transport companies. Together, these transport companies and NYCDEP have permits to use 23 barges and motor vessels for the transport of sewage sludge to the 106-Mile Site. Individual sludge dumping permits are issued for each transport vessel by EPA Region II. Table 2.2 lists the 23 vessels, their ownership, and the sewerage authorities serviced by each vessel.

Of the 23 sludge vessels, only 14 travel to the 106-Mile Site on a regular basis; the remaining 9 are primarily used for sludge transport and transfer within the various New York and New Jersey harbors. The 14 barges that dump regularly have a collective carrying capacity of nearly 46 million gallons of sludge; the total capacity of the 9 standby barges is 5.5 million gallons. Santoro and Fikslin (1987) indicate that the 9 New York and New Jersey sewerage authorities produced 1.5 billion gallons of sludge in 1985. If this volume of sludge were dumped at the 106-Mile Site by the 14 regular carriers, on average, each would be required to make 32 trips to the site.

NYCDEP owns and operates a fleet of four identical barges that have a collective carrying capacity of 14 million gallons of sludge, which is roughly one-third of the total carrying capacity of the 14 barges that regularly transport sludge to the 106-Mile Site.

106-Mile Transport Associates is a consortium of three transportation companies that carry sludge to the 106-Mile Site: Weeks Stevedorings Co., A & S Transportation Co., and General Transport/Standard Marine. Together, these three companies own and operate 15 sludge barges. Nine of these barges are regular dumpers at the 106-Mile Site, with a total carrying capacity of 22.5 million gallons of sludge, and roughly half the carrying capacity of the entire 23-barge fleet.

National Seatrade Inc. owns one large sludge barge and three smaller vessels. Only the large barge, the Seatrader I, regularly transports sludge to the 106-Mile Site. The other vessels are primarily used for sludge transport within harbors, but in rare cases, these small vessels do transport sludge to the 106-Mile Site. The Seatrader I is the largest barge that transports sludge to the 106-Mile Site; its carrying capacity is 9.3 million gallons of sludge, which is approximately 20 percent of the carrying capacity of the entire 14-vessel fleet that regularly dumps sludge at the 106-Mile Site.

TABLE 2.2 SUMMARY OF VESSELS THAT TRANSPORT SEWAGE SLUDGE TO THE 106-MILE SITE. SEWERAGE AUTHORITIES SERVICED BY EACH BARGE OPERATOR ARE INDICATED.

Barge Operator	Vessel	Sewerage Authority
New York City Department of Environmental Protection	Lemon Creek Springs Creek Tibbetts Brook Udalls Cove	New York City Department of Environmental Protection
Weeks Stevedoring Co.[1]	Weeks 701 Weeks 702 Weeks 703 Weeks 704	New Jersey: Passaic Valley, Middlesex County, Bergen County, Linden-Roselle, Rahway Valley, Essex and Union Counties. New York: Westchester County
A & S Transportation Co.[1]	Dina Marie Eileen Kimberley Ann Lisa Maria Veronica Evelyn	same as Weeks
General Transport/Standard Marine[1]	Leo Frank Morris J. Berman Princess B. Rebecca K. Susan Frank	same as Weeks
National Seatrade Inc.	OBI IV Seatrader I Sotoco II E-57	Nassau County Department of Public Works

[1]These owners serve six New Jersey sewerage authorities and Westchester County under a joint venture called 106 Mile Transport Associates.

Table 2.3 presents the sludge carrying capacity for each of the 23 vessels; the 14 vessels that are regular carriers to the 106-Mile Site are listed separately from those that are standby carriers. The standby carriers are much smaller than the regular carriers. Table 2.4 presents the physical dimensions of each of the 23 vessels in the fleet.

Sludge transport vessels have two general hull categories: unpowered barges or motor vessels. Unpowered barges are typically constructed with a pointed bow, a rectangular cross-section, and a flat bottom. Some (including the NYCDEP barges) have a notch in the stern for use by tugs when pushing is necessary in harbors and alongside piers. All unpowered barges are constructed of welded steel and are towed, using a long (≈1/4 mile) towing cable, to the 106-Mile Site. Motor vessels are basically self-powered sludge tankers. These diesel-powered vessels operate under their own control, with nothing in tow.

Typical construction for any vessel transporting liquid includes internal compartmentalization, primarily to prevent instability and capsizing. A cross-section and compartment plan for the New York City barges is shown in Figure 2.1.

2.2.2 Dumping Methods

The vessels that dump sludge at the 106-Mile Site use three different methods of dumping: gravity-induced bottom dumping; pumping; or an eductor system. Regardless of the dumping method, the individual sludge compartments on a vessel are equipped with separate discharge lines, valves, or pumps so that dumping rates can be controlled, either by on-board personnel or, in the case of unmanned barges such as those operated by NYCDEP, by personnel on the towing vessel (tug).

Table 2.5 lists the 14 vessels that regularly transport sludge to the 106-Mile Site and their individual dumping procedures. Bottom dumping is the most common method (11 barges), compared to 2 vessels that pump sludge, and 1 vessel (the Seatrader I) that uses an eductor. A brief description of each dumping method is given below.

TABLE 2.3 SLUDGE CAPACITY OF VESSELS THAT TRANSPORT SEWAGE SLUDGE TO THE 106-MILE SITE.

Barge Operator	Regular Carriers Vessel	Capacity (Short Tons)	Standby Carriers Vessel	Capacity (Short Tons)
New York City Department of Environmental Protection	Lemon Creek	15,000		
	Spring Creek	15,000		
	Tibbetts Brook	15,000		
	Udalls Cove	15,000		
Weeks Stevedorings Co.	Weeks 701	6,400	Weeks 703	4,000
	Weeks 702	17,832	Weeks 704	3,000
A&S Transportation Co.	Eileen	18,132	Dina Marie	2,900
	Kimberley Ann	8,000	Veronica Evelyn	2,900
	Lisa	8,000		
	Maria	7,900		
General Transport/ Standard·Marine	Leo Frank	5,500	Rebecca K.	1,620
	Morris J. Berman	12,000	Susan Frank	
	Princess B.	12,000		
National Seatrade Inc.	Seatrader I	38,528	OBI IV	996
			Sotoco II	954.5
			E-57	6,200

TABLE 2.4 PHYSICAL DIMENSIONS OF VESSELS THAT TRANSPORT SEWAGE SLUDGE TO THE 106-MILE SITE.

Barge Operator	Vessel	Type	Dimensions		Loaded	Sludge
			Length	Width	Draft	Compartments
New York City Department of Environmental Protection	Lemon Creek	Barge	380'	84'	21'-6"	10
	Spring Creek	"	380'	84'	21'-6"	10
	Tibbetts Brook	"	380'	84'	21'-6"	10
	Udalls Cove	"	380'	84'	21'-6"	10
Weeks Stevedoring Co.	Weeks 701	"	266'	56'	11'	8
	Weeks 702	"	400'	80'	25'	10
	Weeks 703	"	290'	53'	16'-8"	8
	Weeks 704	"	78'	43'	13'-7"	8
A&S Transportation Co.	Dina Marie	"	211'	42'-9"	12'-6"	2
	Eileen	"	390'	78'	27'	10
	Kimberly Ann	"	272'	68'	18'-4"	6
	Lisa	"	272'	68'	14'-11"	6
	Maria	"	300'	64'	18'-4"	12
	Veronica Evelyn	"	211'	42'-9"	12'-6"	2
General Transport/Standard Marine	Leo Frank	"	298'	50'	15'	8
	Morris J. Berman	"	303'	90'	15'-10"	9
	Princess B.	M/V	303'	90'	15'-10"	9
	Rebecca K.	Barge	260'	46'-6"	11'	6
	Susan Frank	M/V	260'	46'-6'	11'	6
National Seatrade Inc.	OBI IV	M/V	180'	38'	12'-6"	16
	Seatrader I	Barge	430'	105'	35'-6"	6
	Sotoco II	M/V	180'	38'	13'-6"	14
	E-57	Barge	300'	50'	13'	10

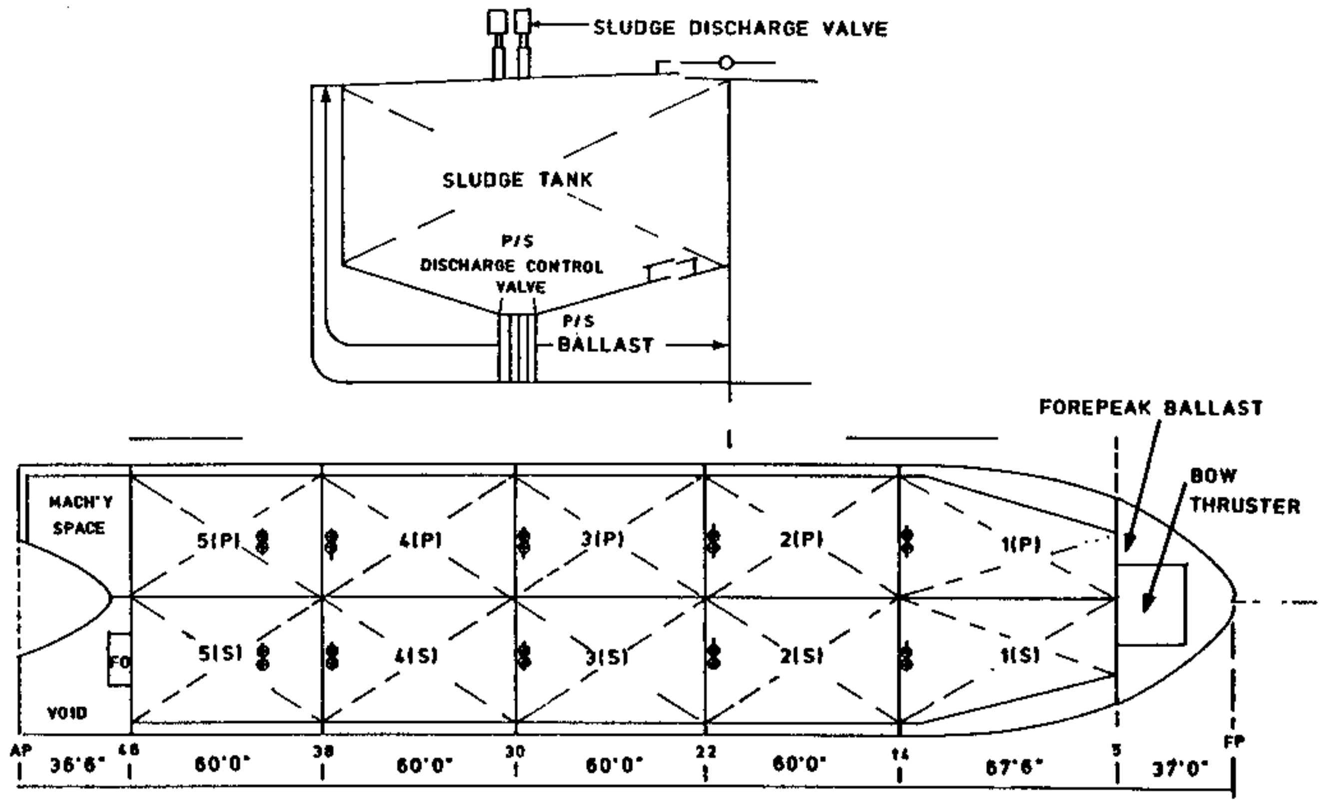

FIGURE 2.1 DIAGRAM OF SLUDGE COMPARTMENTS WITHIN BARGES OPERATED BY THE NEW YORK CITY DEPARTMENT OF ENVIRONMENTAL PROTECTION: REAR VIEW OF PORT SIDE OF BARGE (UPPER); PLAN VIEW (LOWER).

TABLE 2.5 SLUDGE DISCHARGE METHODS AND MAXIMUM RATES FOR VESSELS THAT TRANSPORT SEWAGE SLUDGE TO THE 106-MILE SITE.

Barge Operator	Vessel	Capacity (Million Gallons)	Discharge Method	Average Discharge Duration (h) At 15,500 gal/min	Estimated Maximum Discharge Rate (gal/min)
New York City Department of Environmental Protection	Lemon Creek	3.513	Bottom Dump	4	150,000[1]
	Spring Creek	3.513	Bottom Dump	4	150,000[1]
	Tibbetts Brook	3.513	Bottom Dump	4	150,000[1]
	Udalls Cove	3.513	Bottom Dump	4	150,000[1]
Weeks Stevedoring Co.	Weeks 701	1.504	Bottom Dump	1.5	46,000[2]
	Weeks 702	4.190	Bottom Dump	4.5	139,500[2]
A&S Transportation Co.	Eileen	4.200	Bottom Dump	4.5	31,000[3]
	Kimberly Ann	2.000	Bottom Dump	2	31,000[3]
	Lisa	2.000	Bottom Dump	2	31,000[3]
	Maria	1.850	Bottom Dump	2	31,000[3]
General Transport/ Standard Marine	Leo Frank	1.290	Bottom Dump	1.5	31,000[3]
	Morris J. Berman	2.820	Pump Out	3	31,000[3]
	Princess B.	2.820	Pump Out	3	31,000[3]
National Seatrade Inc.	Seatrader I	9.290	Eductor System	12.5	13,500

[1]Attained if all 20 valves were opened at once.
[2]Capable of discharging full load in 30 minutes.
[3]Rates with valves fully opened.

Bottom Dumping

In bottom-dumping operations, sludge exits the bottom of the barge via dump valve openings that are installed in the bottom of each sludge compartment. Dump valves are hydraulically operated and may be throttled to vary sludge levels in each tank compartment. The sludge dump valves are approved by the U.S. Coast Guard for the specific category of service in which they are utilized. Although the valves can be closed somewhat more than the position used to achieve dumping rates of 15,500 gal/min, extremely low dumping rates would most likely lead to clogging of the valves.

For bottom-dumping barges, the maximum attainable discharge rate is a function of the available pressure head, the viscosities of sludge and seawater, and the configuration and diameter of the dump valve. The rate of discharge varies with the square root of the pressure head, according to the following expression:

$$Q = C\,A\,(2g\,\Delta h)^{\frac{1}{2}}$$

where:
- Q = flow (ft^3/sec)
- C = a constant
- A = discharge area (ft^2)
- g = gravity; 32 ft/sec^2
- Δh = pressure head differential (ft)

Pumping

Sludge is pumped out of the Morris J. Berman and the Princess B. using variable speed, submersible slurry pumps. Discharge rates can be controlled by varying the speed of the pumps. Pump discharge rates are affected by the pressure head in the individual sludge compartment, but the effect of head on discharge rates is much less for pumpers than bottom-dumping barges.

Eductor System

The eductor system used on the Seatrader I is unique. It operates on the principle of aspiration caused by a pressure differential between two fluids. Seawater, serving as the motivating fluid, is pumped into the sludge compartment against the low head of the sludge. Seawater and sludge are consequently mixed to achieve a 1:1 dilution as the mixture is expelled into the receiving water beneath the barge. This process does not require a slurry pump because only clean seawater is pumped into the barge; the sludge mixture exits the barge due to the pressure within the compartment.

The eductor system on the Seatrader I was installed less than 2 years ago, and consequently, its effectiveness and maintenance requirements have yet to be evaluated. It is expected that the eductor system will require less maintenance than standard sludge pumping systems, which use slurry pumps that are prone to mechanical failure.

Table 2.5 also presents the average time for each barge to discharge a full load of sludge, assuming a constant rate of 15,500 gpm. With the exception of the Seatrader I, which requires 12.5 h to dump its load of 9 million gallons, the remaining barges require between 1 and 5 h for dumping.

The maximum attainable discharge rates presented in Table 2.5 are estimates based on information obtained from individual barge operators. Although the individual barge representatives stated that the barges discharge at a maximum rate of 15,500 gpm, they indicated that the barges are capable of discharging at much higher rates. For instance, if the valves were opened for all 10 sludge compartments of a New York City barge, then the discharge rate could reach 150,000 gpm. Only the Seatrader I, which has an eductor system, has a maximum discharge rate that is below the permissible dumping rate of 15,500 gpm.

If dumping rates are to be lowered by factors of 10 or more (see Section 4), representatives from 106-Mile Transport Associates indicate (C. Hunt personal communication) that severe engineering problems will arise. One result is that only one sludge compartment will be dumped at a time, which would pose serious vessel stability problems. Other considerations are given in subsection 5.3.

2.3 NEARFIELD STUDIES OF SLUDGE PLUME BEHAVIOR

This subsection presents a summary of recent field observations within sludge plumes that were dumped at the 106-Mile Site. These observations represent a high-resolution data set for analyses of the nearfield, short-term behavior of sludge plumes. The results were obtained during EPA surveys to the 106-Mile Site in September of 1987 and 1988 (EPA , 1992c; 1988b). Although information was acquired on the physical behavior and transport of sludge plumes during the nearfield survey in March 1988, the chemical data from the survey were insufficient for accurate determinations of sludge dilution versus time.

The primary scientific objectives of the two September surveys were to

- Track a specific portion of a sludge plume to monitor its movement within and outside of the 106-Mile Site.
- Remain with the plume for at least 4 h for collection of water samples for analyses of chemical and biological tracers and total suspended solids.
- Conduct in situ measurements of near-surface currents and water properties to identify physical features and processes that may affect sludge plume behavior and transport.
- Acquire water samples for analysis to determine actual concentrations of sludge components in a plume. Results are to be used for testing compliance with marine water quality criteria and calculating rates of sludge dilution.
- Perform all sampling activities for a number of sludge plumes to acquire statistics on plume behavior for different barges under various oceanographic conditions.
- Evaluate shipboard instrumentation and sampling procedures for their suitability in monitoring of sludge plumes.

A major factor that contributed to the success of these surveys was the instrumentation used for in situ sampling within the sludge plumes. In order to achieve rapid, high-resolution measurements of physical water properties concurrently with the collection of water samples for chemical analyses, a seawater pumping system was integrated with a CTD (conductivity-temperature-depth) profiling system. With the real-time sampling and display capabilities of this system, it was possible to locate the most concentrated parcels of sludge within the plume and position the underwater unit at the depth of the turbidity maximum, which was indicative of the highest concentrations of sludge. Thus, the profiling activities yielded accurate measurements of

- Plume depth and thickness as a function of time, from which plume cross-sectional area, and plume-averaged dilution can be estimated.

- Concentrations of chemical and biological tracers within samples of plume water, from which sludge dilution can be estimated for the most concentrated parcels of sludge within a plume.

Figure 2.2 presents a time series plot of sludge dilution derived from data collected during plume event DB-3 on September 3, 1987. Note that dilution is plotted on a logarithmic scale to accommodate the wide range of dilutions observed during the 9-h survey. This figure presents information on the plume-averaged dilution (solid circles) as well as the dilution of discrete parcels of plume water (open symbols), derived from analyses of trace metals.

Plume-averaged dilutions, derived from the cross-sectional area of the plume and the average dumping rate per unit of plume length, suggest a high rate of dilution during the first 2 h after dumping. Initial dilutions (within 5 min after dumping) were approximately 2,500:1; dilutions 30 min and 2 h after dumping were on the order of 10,000:1 and 80,000:1, respectively.

As indicated in Figure 2.2, the plume-averaged dilutions were much greater than dilutions derived from chemical analyses of water samples collected within the core of the plume. One may suspect that the high plume-averaged dilutions were a result of overestimating the width of the plume, but the error associated with this estimate is less than 10 percent. During the first 2 h after disposal, the plumes spread laterally, but they remained intact, such that horizontal turbidity profiles along the plume transects exhibited no significant patches of "clean" receiving water inside the distinct outer edges of the plume. Thus, these high plume-averaged dilutions were not a consequence of "streaking" of the plume and overestimation of plume width.

Detailed analyses of turbidity data within the individual plume transects have revealed that the highest sludge concentrations are maintained within a concentrated core which, on a volume basis, represents a small percentage of the plume. As illustrated by the open symbols in Figure 2.2, discrete parcels of sludge from the core of the plume were much less dilute than the "average plume" derived from the plume dimensions. At the various

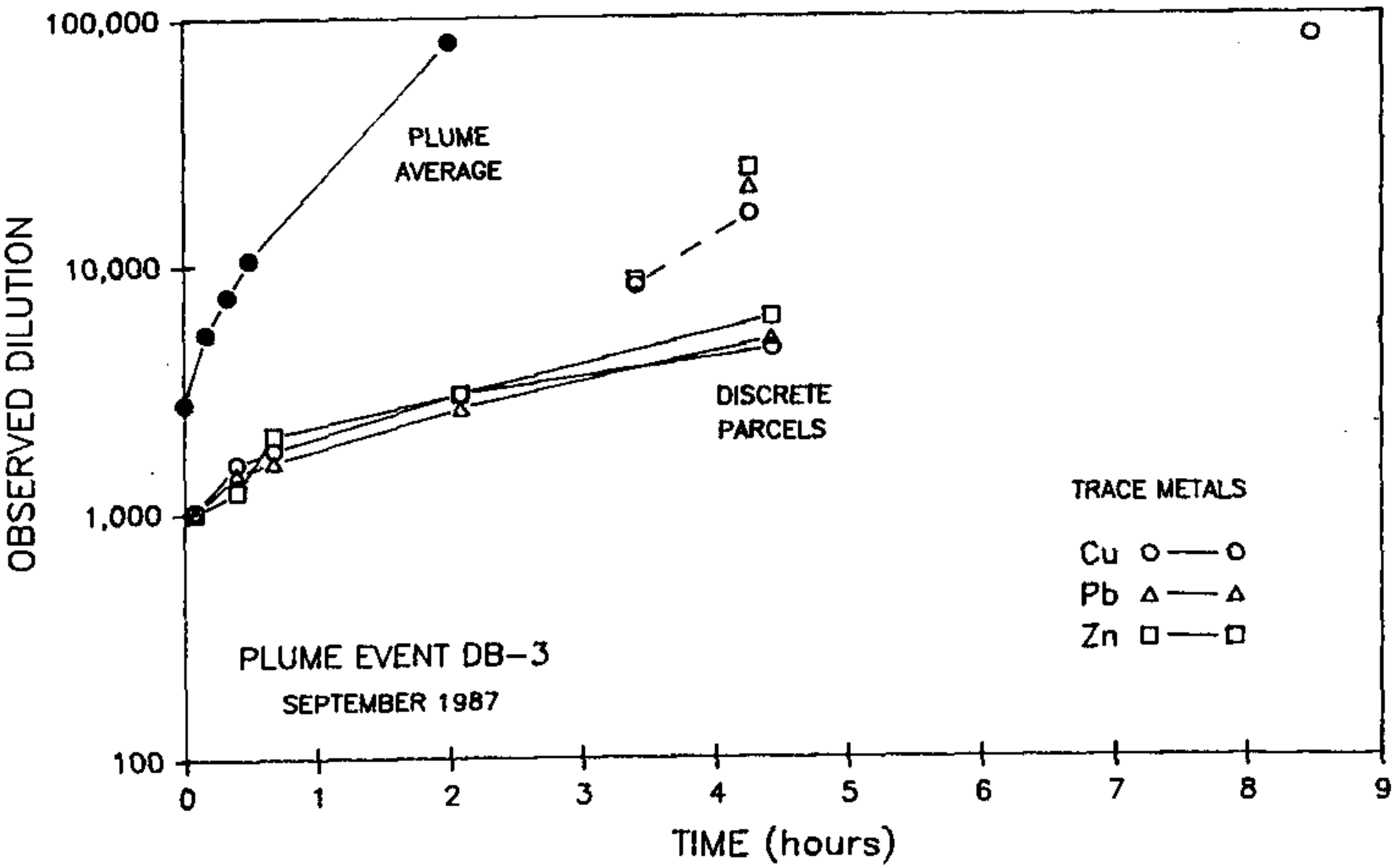

FIGURE 2.2 TIME HISTORY OF SLUDGE DILUTION WITHIN PLUME EVENT DB-3 AT THE 106-MILE SITE DURING SEPTEMBER 1987. SOLID CIRCLES REPRESENT AVERAGE DILUTION OF ENTIRE PLUME; OPEN SYMBOLS REPRESENT TRACE METALS RESULTS FROM DISCRETE WATER PARCELS WITHIN THE CORE OF THE PLUME.

sampling times indicated, separate analyses of copper, lead, and zinc were performed on the samples collected within the most concentrated portion of the plume. Dilutions were calculated by dividing the measured concentrations of a trace metal by the mean concentration of that specific trace metal within sludge generated by the Port Richmond treatment facility (Santoro and Fikslin, 1987), which was the source of the sludge dumped during event DB-3. The final report for the September 1987 survey (EPA , 1992c) provides detailed information on sludge dilution calculations.

The solid lines connecting the trace metal results in Figure 2.2 illustrate that (1) parcel dilutions were much lower than plume-averaged dilutions, (2) the rate of dilution of concentrated parcels was much less than the rate of plume-averaged dilution during the first 4 h after the dump, and (3) the results from three trace metals were very similar. Within 5 min after dumping, parcel dilutions were roughly 1,000:1; at 4.4 h, parcel dilutions were on the order of 4,500:1. The higher sludge dilutions indicated at 3.4 and 4.3 h were obtained from water parcels situated outside the most concentrated portion of the sludge plume, and consequently, they are not appropriate in estimating minimum dilution.

Beyond 5 h after dumping for event DB-3, the sludge plume was broken into patches of undetermined sizes. Using the real-time sampling system, it was possible to locate relatively concentrated parcels of sludge water between 5 and 9 h after dumping, but there was no way to ensure that a single parcel was being surveyed repeatedly. Chemical analyses of the most concentrated portion of sludge water located 8.5 h after the dump demonstrated a parcel dilution of 77,000:1 (Figure 2.2). Attainment of these dilutions required an increase in the rate of dilution over the rate that is demonstrated between 1 and 4 h. This accelerated dilution was most likely attributed to the break-up of the plume; with the directed sampling capability during the survey, we are relatively confident that this sample was taken from the most concentrated portion of the plume that existed at the time of the observation.

Figure 2.3 presents a conceptual diagram (with linear dilution axis) of the three phases of plume dilution that may have occurred during event DB-3: initial, wake-induced mixing, gradual oceanic mixing, and accelerated mixing after plume break-up. The solid line in this figure represents a

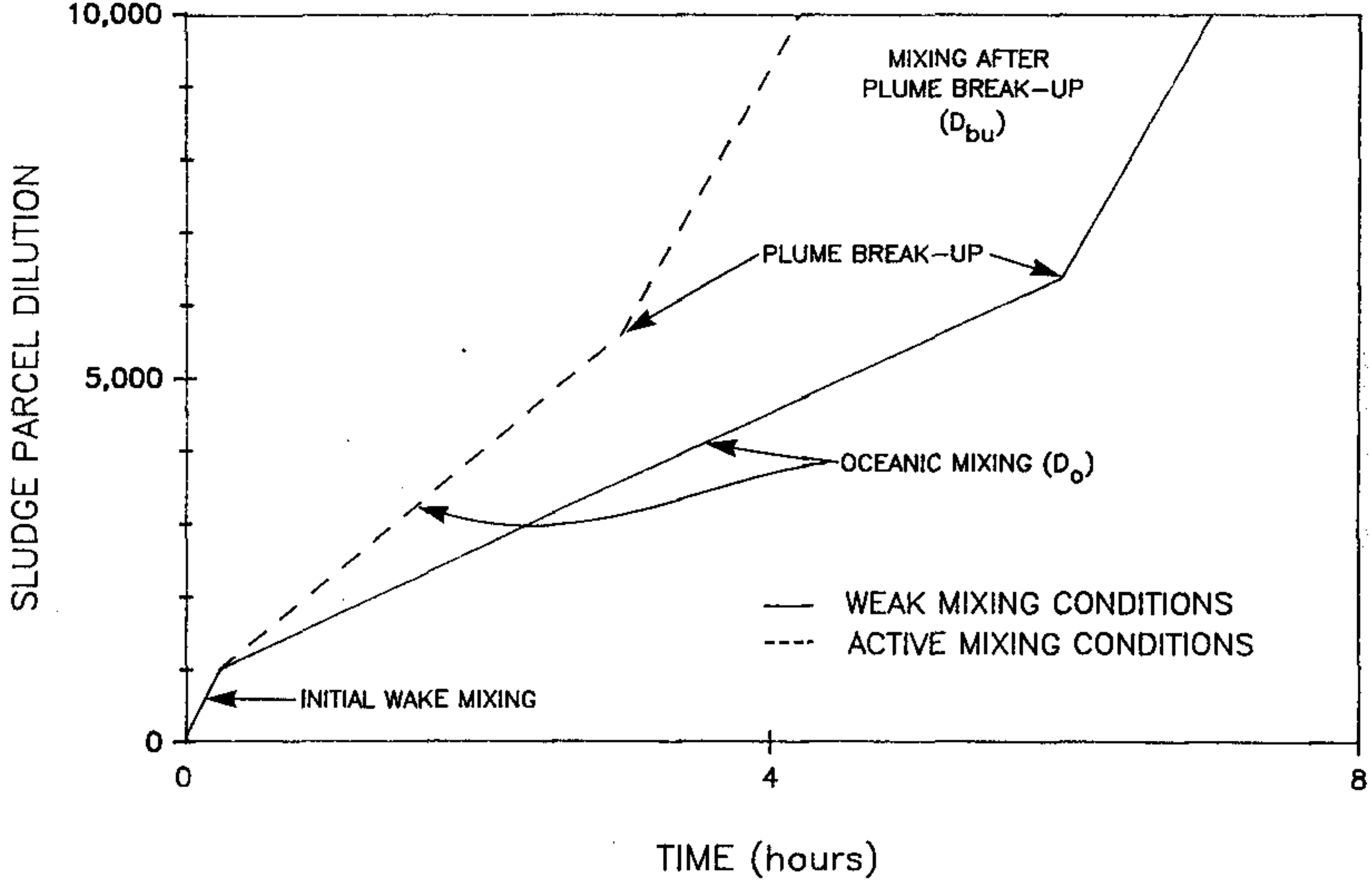

FIGURE 2.3 CONCEPTUAL DIAGRAM OF THE DILUTION OF SLUDGE PARCELS WITHIN PLUMES FOR TWO CASES OF MIXING CONDITIONS.

hypothetical case of weak mixing conditions (e.g., low winds, calm seas) such as those encountered during plume event DB-3. Plume break-up and accelerated dilution apparently occurred after 4 h. The broken line in Figure 2.3 represents a case of active mixing, whereby the rate of oceanic mixing would be greater than the rate during weak mixing conditions. During active mixing, plume break-up may occur well before 4 h.

All four of the plumes monitored during the September 1987 survey exhibited dilution characteristics similar to those representing weak mixing conditions in Figure 2.3. Although the linear plumes began to break up 2 or 3 h after dumping, concentrated patches of plume water remained relatively intact for periods longer than 4 h. For example, Figure 2.4 presents minimum dilutions of plume DB-3, based upon field-measured copper concentrations and mean copper values of sludge described by Santoro and Fikslin (1987). With dilutions presented on a linear axis, it is evident that the rate of parcel dilution from initial mixing (5 min after dumping) to 4 h was quite constant (≈900 per h).

The dilution estimates given in Figures 2.2 and 2.4 provide a realistic representation of the short-term behavior of plume event DB-3, but three factors contribute errors to these minimum dilution estimates: (1) spatial sampling problems; uncertainties in having sampled the maximum concentration within the plume at a given time, (2) laboratory/analytical errors during processing and analysis of trace metal samples, and (3) uncertainties in the actual metals concentration in the sludge that was dumped. Positioning errors cannot be quantified, but missing the maximum concentration will result in higher apparent dilutions than actually exist within the core of the plume. Laboratory errors are small (<10%), but uncertainties in sludge constituent concentrations are large. Constituent concentrations of the dumped sludge were not measured; dilutions were calculated from published values of constituent concentrations in sludge. Santoro and Fikslin (1987) estimate that mean copper concentrations in Port Richmond sludge are 50.9 mg/L with a standard deviation of 36% of the mean. Thus, with ±1 standard deviation about the mean, copper concentrations could range from 32.6 to 69.2 mg/L for the Port Richmond facility. This variation in copper concentration may also result in a ±36 percent uncertainty in the rate of dilution after initial wake mixing (e.g., 900 ±324 per hour).

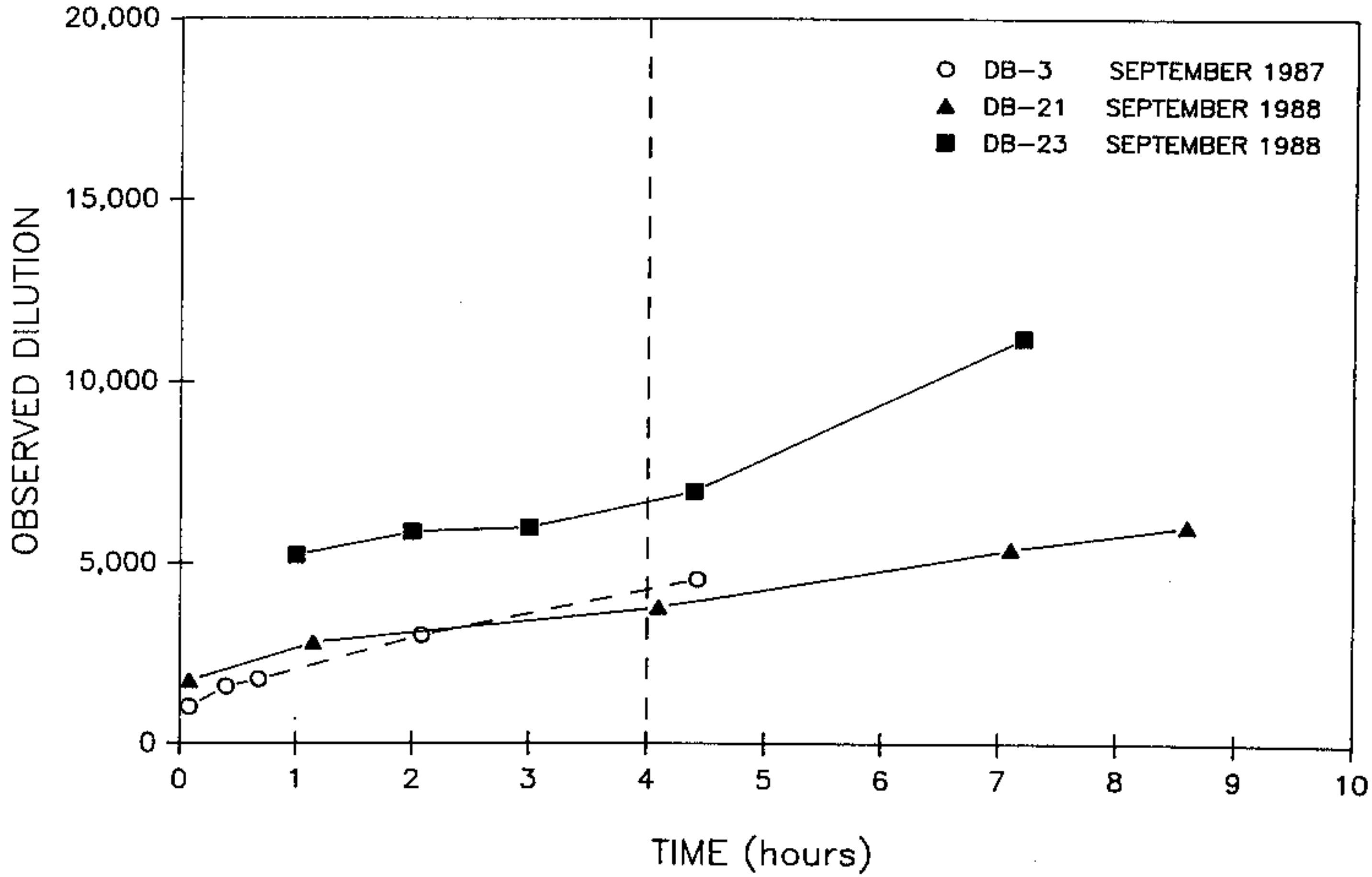

FIGURE 2.4 TIME HISTORY OF OBSERVED SLUDGE DILUTION WITHIN THE CORE OF SLUDGE PLUMES SURVEYED IN SEPTEMBER 1987 AND 1988. DILUTIONS ARE BASED UPON COPPER CONCENTRATIONS WITHIN WATER SAMPLES.

To reduce these errors during the September 1988 survey, sludge samples were obtained from the individual barges that transported sludge to the site during the survey. Trace metals analyses of (1) the barge (sludge) samples and (2) water samples collected from the core of the plumes during the nearfield survey yielded direct estimates of the time rate of dilution of the sludge plumes.

In addition to the dilution results from September 1987, Figure 2.4 presents dilution information from plume events DB-21 and DB-23 monitored during the September 1988 nearfield survey (EPA , 1988b). As discussed above, the 1988 results were derived from the ratio of copper concentrations in plume water samples to those determined from analyses of 100% sludge. This figure illustrates that both the range and the rate of change of dilution were very similar for plume events DB-3 and DB-21. Table 2.6 indicates that initial dilutions (≈5 min after dumping) were 1,018:1 and 1,724:1 for plume events DB-3 and DB-21 respectively; dilutions for both were near 4,000:1 4h after dumping. The results from plume event DB-21 also illustrate that the rate of core dilution remained relatively constant for more than 8h.

The dilution results from plume event DB-23 exhibited a similar rate of dilution during the period from 1 to 4h after dumping, but the extent of the dilution was roughly twice that of plume events DB-3 and DB-21. We suspect this offset was due to uncertainties in the copper concentration of the sludge that was dumped in the portion of the plume surveyed (the barge samples were collected prior to transit to the 106-Mile Site and various compartments of sludge could have had different chemical characteristics).

TABLE 2.6 OBSERVED DILUTIONS AND RATES OF DILUTION FOR SLUDGE PLUMES SURVEYED IN SEPTEMBER 1987 AND 1988.

Plume Survey	Date	Observed Dilutions				Rate of Dilution (1/h)	
		5min	1h	4h	7h	t=1h to 4h	t=5min to 4h
DB-3	9-87	1,018	2,055	4,258	-	734	827
DB-21	9-88	1,724	2,629	3,717	5,303	363	508
DB-23	9-88	-	5,200	6,664	10,887	488	610[a]

[a]Estimated value.

3. DEVELOPMENT OF DUMPING RATE EQUATION

One of the primary objectives of this work assignment is to use existing information (in this case, field data rather than predictive models) to determine the rate at which sludge plumes are diluted at the 106-Mile Site. Field measurements of short-term sludge dilution are necessary in order to determine whether dumping operations are in compliance with EPA water quality criteria, but the results can also be used to develop a conceptual dilution model that will allow prediction of optimum sludge dumping rates which, in turn, will achieve the dilutions required by the water quality criteria. The process of developing a realistic model of sludge dilution entails a number of steps:

1. Utilization of the field results from the nearfield studies at the 106-Mile Site to determine the rate of change of sludge concentration within the plumes, and hence, the rates of sludge dilution.

2. Identification of the major physical processes responsible for sludge plume dilution, followed by formulation of an empirical model for dilution of sludge parcels based upon the existing field observations.

3. Application of the empirical model of sludge dilution for prediction of the rate at which sludge should be dumped in order to achieve dilutions that satisfy EPA water quality criteria.

4. Identification of the major sources of variability (e.g., oceanographic conditions, barge dumping characteristics, and sludge characteristics) that will affect sludge dilution yet cannot, at the present time, be quantified, given the limited set of field observations.

5. Recommendation of additional field measurements that will facilitate better predictions of sludge dilution, and consequently, more defensible rates for dumping of sewage sludge at the 106-Mile Site.

The following discussion addresses the formulation of the empirical model of sludge dilution and the assumptions made during its development.

3.1 SLUDGE PLUME DILUTION

The field observations of sludge parcel dilution, which were presented in Subsection 2.3, indicate three phases of mixing during the first 8 h after dumping: (1) an initial period (from 0 to ≈5 minutes after dumping) of turbulent, wake-induced mixing, (2) a gradual phase of relatively slow mixing primarily due to oceanographic processes, and (3) an accelerated mixing phase when the sludge plume is broken up and sludge parcels from the interior of the plume are actively mixed with clean receiving water. Dilution, D, at any time, T, after dumping can therefore be estimated from an expression which contains the three observed phases of mixing:

$$D = D_i + \frac{dD_o}{dt} \times T\Big|_{0}^{bu} + \frac{dD_b}{dt} \times T\Big|_{bu}^{t} \qquad (1)$$

where

D = the dilution of sludge parcels at any time, T, after initial wake-induced mixing

D_i = the dilution achieved (at T≈5 min) from initial, wake-induced mixing

$\frac{dD_o}{dt}$ = the time rate of change of sludge parcel dilution during the time from dumping (T=0) to the time at which the plume breaks up (T=bu)

T = time after dumping

$\frac{dD_b}{dt}$ = the time rate of change of sludge parcel dilution during the period after plume break-up (T=bu)

The time at which a sludge plume starts to physically break up is highly dependent upon oceanographic conditions, sludge characteristics, barge dumping characteristics, and other physical, chemical, and engineering factors. Under extreme conditions of high waves and current shear, plumes may break up within 1 to 2 h after dumping, but during weak mixing conditions, plumes may remain relatively intact for periods of 4 h or longer.

The field observations of plumes during September 1987 and 1988 were made during relatively calm sea and mixing conditions, and consequently, the effect of plume break-up on parcel dilution was not substantial until many hours (>> 4 h) after dumping. Additional surveys of sludge plume behavior will be required to develop a statistical estimate of the time at which plumes break up, but based upon the limited field data, we can assume that a significant number of sludge plumes will remain relatively intact for at least 4 h. This type of plume behavior would be appropriate for development of a model that predicts the minimum dilution of sludge parcels at any time after dumping.

If we are concerned about the conservative behavior of sludge plumes and dilution only up to 4 h after dumping, then Eq.(1) reduces to

$$D = D_i + \left.\frac{dD_0}{dt} \times T\right|_0^{4h} \qquad (2)$$

This simplified expression represents the two-phase behavior of sludge parcel dilution prior to plume break-up: dilution at 4 h is achieved by an initial phase of rapid dilution (to achieve dilution D_i), followed by a slower phase of oceanographic mixing and dilution.

3.1.1 Wake-Induced Initial Mixing

Mixing of sludge within the wake of the barge is extensive during the first few minutes after dumping. Much of this mixing (and sludge dilution) is attributed to the turbulence of the receiving water immediately behind the barge, but within 5 to 10 minutes after dumping, the momentum of the wake diminishes and other factors govern plume mixing and dilution.

During the period of initial (0 to ≈5 min) mixing, wake momentum may be the most important factor, but there are additional parameters/processes that affect mixing and dilution. Initial, wake-induced dilution, D_i, is expected to be a function of the following parameters:

$$D_i = f [R, B, S, Z, M_W] \quad (3)$$

where

- R = the effective dumping rate: the amount of sludge dumped per unit of track (plume) length, expressed in units of gal/ft
- B = the effect of barge characteristics (size, speed, draft, depth of discharge port) and dumping method (bottom dump, pump, or eductor)
- S = sludge characteristics (specific gravity, solids content, ability to flocculate, density relative to receiving water)
- Z = pycnocline depth
- M_W = mixing (dispersion) due to winds and waves

Determination of the relative effects of these parameters on initial (0 to ≈5 min) sludge dilution would require rapid, intensive field measurements of plume mixing over a wide range of dumping rates, barge types, dumping methods, sludge types, stratification regimes, and oceanographic mixing regimes. Because this research activity is well beyond the scope of the EPA Ocean Dumping program, we will represent initial (0 to ≈5 min), wake-induced dilution as a single parameter, D_i, in the reduced equation for sludge dilution (see Eq. 2). With the field results from the past nearfield monitoring surveys, it is possible to estimate initial dilution, D_i, 5 min after dumping, but we cannot determine the relative importance of the individual parameters in Eq. (3).

To facilitate future comparisons between initial dilution rates from other monitoring surveys, the various engineering and environmental conditions encountered during plume event DB-21 (September 1988) are summarized below.

- R effective dumping rate was 22.85 gal/ft, based upon an average dumping rate of 10,855 gal/min at a barge speed of 4.7 kn.
- B barge configuration was that of the <u>Princess B</u>, which pumps sludge out of its side; this barge has a maximum draft of 15 ft and a beam of 90 ft.

S the sludge within the barge was from Passaic Valley; the specific gravity of the sludge (≈1.004) was less than that of the receiving water (≈1.023), which had water properties of ≈22°C and ≈33 ppt.

Z the seasonal pycnocline at the 106-Mile Site was strong and shallow, situated between roughly 25 and 40 m.

M_W surface mixing conditions were mild, due to calm (<3 ft) seas and winds less than 15 kn.

As indicated in subsection 2.3, the initial dilution of sludge parcels 5 min after dumping for plume event DB-21 was estimated at 1,724:1 from analyses of trace metals data. Because the relative effects of the various parameters in the initial dilution equation (Eq. 3) are unknown, we can only speculate on how the rate of initial dilution would change under different dumping and environmental conditions:

M_W Had the sea and wind conditions been more severe (i.e., during winter storm events) initial dilution might have been significantly greater due to increased dispersion.

Z The observed sludge plume might have settled somewhat deeper, and dilutions might have been greater had there been no seasonal pycnocline. Preliminary results of the winter survey indicate, however, that sludge dumped at rates near 15,000 gal/min does not settle deeper than about 30 m in the first 8 h following dumping.

S Other than from laboratory studies, little is known about the settling characteristics of the various sludges dumped at the site. Nevertheless, the saline receiving water will, during all seasons, be much more dense than the sludge dumped at the site, such that all plumes will be relatively buoyant and variations in sludge settling characteristics may have a second-order effect upon initial dilution.

B The Princess B, which pumps sludge out of one side of the vessel, may have somewhat different initial mixing characteristics than barges which are bottom dumpers, but the available field results from barges of different configurations suggest that initial dilution may be relatively insensitive to dumping method.

In summary, the environmental conditions (parameters M_W and Z) during plume event DB-21 represent mild conditions for sludge dilutions (conditions that produce low dilutions). Because the object of the present analysis is to derive a model for prediction of worst-case (lowest) dilutions, the field data from event DB-21 are appropriate for development of the model.

For the purpose of developing a conservative model, we will assume that (1) all sludges will behave similarly during the first few minutes after dumping, and (2) the rate of initial mixing is generally the same for all barge configurations. With these assumptions, the only parameter remaining that will appreciably affect the wake-induced dilution, D_i, is the effective dumping rate, R. We expect that dilution is inversely proportional to effective dumping rate, such that we obtain the following expression for initial dilution:

$$D_i = f\,(1/R)$$

The recent field observations of plume width within the wake of barges indicate that, during the initial period of wake-induced mixing, the sludge plume is confined within the turbulent mixing volume created by the barge wake. For the New York barges, the initial plume is as wide as the barge wake, but for other barges such as the Princess B, the plume is a fraction of the wake width. Therefore, we may assume that the initial (t=0) mixing volume behind a barge has an upper limit equal to the volume of the barge wake (roughly the barge width times the draft), and to a first-order approximation, the average dilution would be inversely proportional to the volume of material dumped in the wake (the effective dumping rate, R). In the absence of short-term (0 to 5-min) measurements behind the various barges, we will consider the initial mixing regime as a linear system such that

$$D_i = A/R$$

where A = a constant relating dilution to effective dumping rate

This linear expression can then be used to predict effective dumping rates from observed dilutions and known dumping rates:

$$[R \times D_i]_{obs} = A = [R \times D_i]_{req}$$

or

$$R_{req} = \frac{[R \times D_i]_{obs}}{[D_i]_{req}} \tag{4}$$

where R_{req} = the effective dumping rate that will be required to achieve a specific dilution

D_i req = the required initial dilution (at t≈5 min) based upon compliance with water quality criteria at 4 h

and 'obs' refers to observed initial dilutions and average effective dumping rates from plume event DB-21

This expression will be used later, in conjunction with Eq. (2), to obtain an empirical equation for determining dumping rates which are based upon (1) dilutions required to prevent selected sludge constituents from exceeding water quality criteria at 4 h, (2) observations of initial dilution, and (3) observed rates of oceanic mixing and sludge dilution.

3.1.2 Oceanic Mixing

After the initial (0 to ≈5 min) period of wake-induced turbulent mixing, sludge plumes are diluted at slower rates as a result of buoyancy effects, sludge flocculation and settling, and oceanic dispersion processes. Under extreme wind and wave conditions, near-surface plumes may be dispersed at rates that approach the rates achieved during wake-mixing, but most of the time, oceanic dispersion is relatively slow. For the period following wake-induced mixing, the factors expected to control the rate of sludge dilution, $\frac{dD_o}{dt}$, are given below:

$$\frac{dD_o}{dt} = f[D_i, S, Z, M_w, M_c] \tag{5}$$

where D_i = the extent of wake-induced initial dilution

S = sludge characteristics (e.g., flocculation and settling)

Z = pycnocline depth

M_w = dispersion due to winds and waves

M_c = dispersion due to current shear

D_i, the initial dilution 5 minutes after dumping, is an important factor in the longer-term (5 min to 4 h) dilution phase because, if the effective dumping rate is high and the dilution is low, the core of the plume will be more concentrated and achievement of a specified (high) dilution will require a longer period of time.

Sludge characteristics, pycnocline depth, and surface mixing due to winds and waves will affect sludge dilution as described during the phase of initial mixing. Dispersion due to current shear was not expected to have a major effect upon dilution during the first few minutes after dumping, because the turbulence due to barge momentum is much greater than the effective mixing due to current shear. However, after the wake has lost its momentum, current shear, if present, can effectively increase dilution by lateral displacement of portions of the plume.

During plume event DB-3 (September 1987), strong current shear at the base of the surface mixed layer effectively increased the rate of dilution within the plume. Had the current shear been weak or nonexistent (which may be the typical case except during the passage of warm-core eddies), the rate of plume dilution might have been less. During the September 1988 survey (plume events DB-21 and DB-23), there was no significant current shear at the base of the mixed layer. As indicated in Table 2.6, the rate of dilution from 0 to 4 h for DB-21 and DB-23 was significantly less than observed for DB-3, but we cannot be sure this difference was mainly attributed to the lack of current shear.

To summarize, although we can identify the physical factors/processes that affect the rate of sludge plume dilution, $\frac{dD_o}{dt}$, after the period of initial, wake-induced mixing, we do not have sufficient field data to quantify the effects of each process in Eq. (5). We will therefore estimate the rate of dilution, $\frac{dD_o}{dt}$, from specific field data of representative sludge plumes. As discussed in subsection 2.3, the results from plume event DB-21 provide the most conservative (lowest) rate of dilution during the first 4 h following dumping: ≈ 500:1/h. This rate will be used in the following section.

3.2 DUMPING RATE EQUATION

Derivation of an empirical equation for prediction of optimum dumping rates requires combination of Eqs. (2) and (4):

$$D_{wqc} = D_{i\,req} + \frac{dD_o}{dt} \times T \Big|_{t=0}^{t=4} \qquad (2)$$

or

$$D_{i\,req} = D_{wqc} - \frac{dD_o}{dt} \times T \Big|_{t=0}^{t=4} \qquad (2')$$

and

$$D_{i\,req} = \frac{R_{obs} \times D_{i\,obs}}{R_{req}} \qquad (4')$$

Combining Eqs. (2') and (4') yields

$$\boxed{R_{req} = \frac{R_{obs} \times D_{i\,obs}}{D_{wqc} - \frac{dD_o}{dt} \times T \Big|_{t=0}^{t=4}}} \qquad (6)$$

where R_{req} = the required effective dumping rate to achieve a specified 4 h dilution, D_{wqc}, that is based upon water quality criteria

D_{wqc} = the dilution at 4 h that is required by the water quality criteria

R_{obs}, $D_{i\ obs}$ = field observations of plume event DB-21 during September 1988

The underlying concepts and assumptions inherent in this empirical dumping rate equation (Eq. 6) are illustrated in Figure 3.1. This figure schematically represents the observed time series of sludge parcel dilution from plume event DB-21 (lower line), as well as the required dilution (upper line) that would be necessary to achieve a 4 h dilution, D_{wqc}, of 20,000:1. Note that this dilution of 20,000:1 is merely an example; actual dilution requirements for each permit applicant are given in subsection 4.1.

This conceptual dilution model (Eq. 6) is based on two assumptions:

- The rate of oceanic dilution from 0 to 4 h, $\frac{dD_o}{dt}$, is equivalent for the observed and required dilution cases.

- The required initial dilution (at T≈5 min), $D_{i\ req}$, can be achieved by a linear reduction in the effective dumping rate, R.

Thus, if D_{wqc} (at 4 h) can be specified by water quality criteria, then Eq. (6) can be used to predict the effective dumping rate, R_{req}, that would achieve the required dilution at 4 h. A sample calculation is provided below.

Using the results of plume event DB-21:

R_{obs} ≈ 22.8 gal/ft (10,855 gal/min ÷ 4.7 kn ÷ 101.3 ft-h/min-nmi)

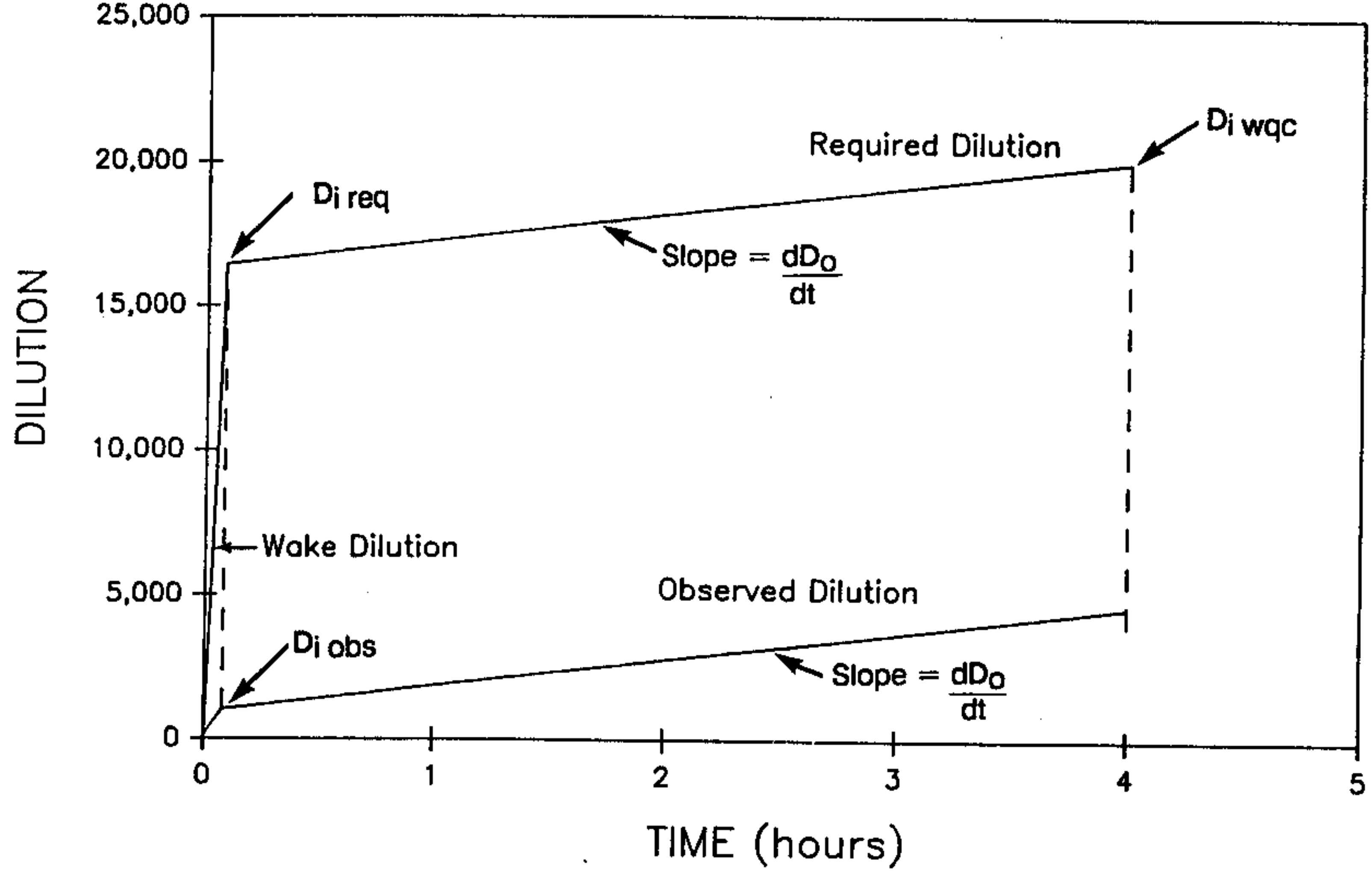

FIGURE 3.1 CONCEPTUAL MODEL OF SLUDGE PLUME DILUTION FROM OBSERVATIONS (LOWER LINE) DURING PLUME EVENT DB-21. IF A DILUTION OF 20,000 IS REQUIRED BY WATER QUALITY CRITERIA AT 4 h, THEN THE REQUIRED DILUTION IS REPRESENTED BY THE UPPER LINE.

$$D_{i\ obs} \approx 1{,}724$$

$$\frac{dDo}{dt} \approx 500 \text{ per hour}$$

$$\frac{dD_o}{dt} \times T \Big|_{t=0}^{t=4} = 500 \times 4 \text{ h} = 2{,}000$$

and, if the water quality criteria (e.g., for copper), require a dilution of 20,000:1 at 4 h:

$$D_{\ wqc} = 20{,}000$$

then, using Eq. (6) we obtain

$$R_{\ req} = \frac{22.8 \times 1{,}724}{20{,}000 - 2{,}000}$$

$$R_{\ req} \approx 2.2 \text{ gal/ft}$$

for the effective dumping rate that would be required to meet water quality criteria, based upon the field observations from plume event DB-21.

To determine the volume dumping rate, in units of gallons per minute, requires multiplication of the effective dumping rate by the average barge speed during the dumping operation:

$$V_{DR} = R_{\ req} \times K \times 101.3 \ \frac{\text{ft-h}}{\text{min-nmi}} \qquad (7)$$

where V_{DR} = the volume dumping rate (gal/min)

$R_{\ req}$ = the required effective dumping rate (gal/ft)

K = barge speed (kn)

During plume event DB-21, the barge Princess B was traveling at 4.7 kn such that the volume dumping rate should have been

$$V_{DR} = 2.2 \text{ gal/ft} \times 4.7 \text{ kn} \times 101.3$$

$$\approx 1{,}047 \text{ gal/min}$$

to achieve a dilution of 20,000:1 at 4 h after dumping. Note that if the barge speed had been 3 kn, the volume dumping rate would have to be lowered to 668 gal/min (3/4.7 x 1,047).

Combination of Eqs. (6) and (7) yields the complete expression for determination of volume dumping rates from field observations of event DB-21 in September 1988.

$$V_{DR} = \frac{101.3 \times K \times R_{obs} \times D_{i\ obs}}{D_{wqc} - \left.\frac{dD_o}{dt} \times T\right|_{t=0}^{t=4}}$$

and since $V_{obs} = R_{obs} \times K \times 101.3$

then

$$\boxed{V_{DR} = \frac{V_{obs} \times D_{i\ obs}}{D_{wqc} - \left.\frac{dD_o}{dt} \times T\right|_{t=0}^{t=4}}} \qquad (8)$$

Substitution of results from plume event DB-21 yields

$$V_{DR} = \frac{10,855 \times 1,724}{D_{wqc} - 500 \times 4} = \frac{1.8714 \times 10^7}{D_{wqc} - 2,000} \quad \text{(gal/min)}$$

Section 4 presents sludge dumping rates that are based upon various values of D_{wqs} in the above expression. Note that this equation assumes a barge speed of 4.7 kn (equivalent to that during plume event DB-21). To determine the volume dumping rate, V_{DRS} at any barge speed, S, the rate for 4.7 kn (for V_{DR}) can simply be multiplied by the ratio of speeds:

$$V_{DRS} = V_{DR} \times \frac{S}{4.7}$$

The following subsection demonstrates the importance of barge speed to the volume dumping rate (in gal/min).

3.3 BARGE SPEED CONSIDERATIONS

When considering sludge dumping rates, the most important point to remember is that plume dilution and compliance with water quality criteria are more dependent upon the **effective dumping rate (in gal/ft)** than the volume dumping rate (in gal/min). For a given volume dumping rate, barges that travel relatively fast (5 to 8 kn) effectively dump much less sludge per unit track length than do barges that travel slower.

Present EPA regulations for dumping of sewage sludge at the 106-Mile Site specify (1) a maximum volume dumping rate, V_{DR}, of 15,500 gal/min, and (2) a minimum barge speed of 3 kn. Compliance with these regulations is represented by the shaded region in Figure 3.2.

Under specific dumping conditions of 15,500 gal/min and 3 kn, the effective dumping rate, R, is 51 gal/ft. Also shown in Figure 3.2 is a line indicating the set of barge speeds and volume dumping rates (in gal/min) that satisfy the case of R = 51 gal/ft. The shaded region illustrates that compliance with EPA dumping regulations (which are based upon volume dumping rates and barge speeds) will normally result in effective dumping rates that are well below the implied maximum rate of 51 gal/ft. For instance, if barges dump at 15,500 gal/min while traveling at speeds >3 kn, the following effective dumping rates, R, result:

At 6 kn and 15,500 gal/min, R = 25.5 gal/ft
At 9 kn and 15,500 gal/min, R = 17.0 gal/ft

Thus, if the requirement were to achieve an effective dumping rate of 51 gal/ft, the volume dumping rates, V, could be increased as follows:

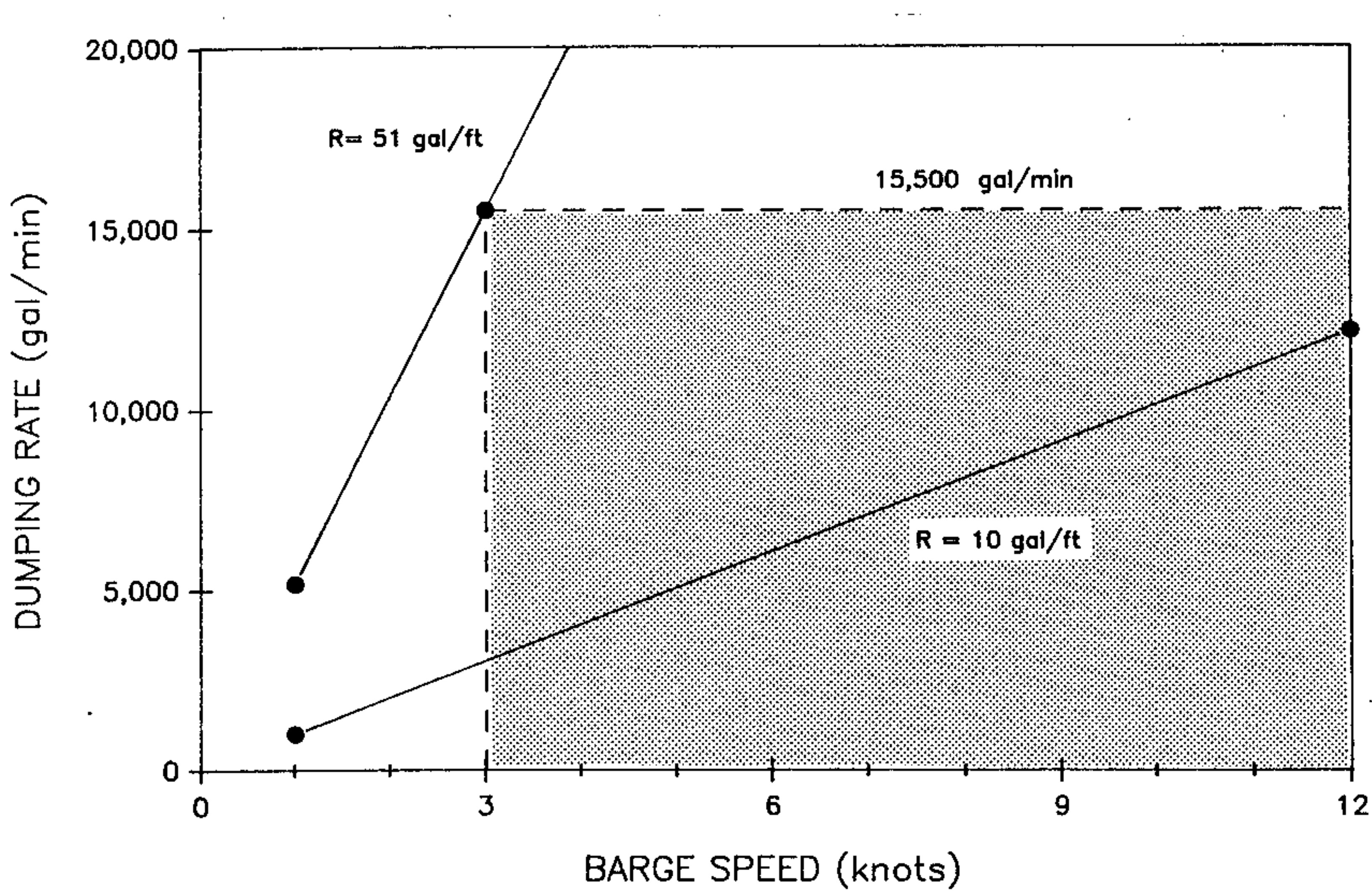

FIGURE 3.2 PLOT OF VOLUME DUMPING RATE (GAL/MIN) VERSUS BARGE SPEED. THE SHADED REGION REPRESENTS EPA DUMPING REGULATIONS. SOLID LINES REPRESENT TWO VALUES OF THE EFFECTIVE DUMPING RATE IN UNITS OF GAL/FT.

To achieve R = 51 gal/ft at 6 kn, V = 31,000 gal/min
To achieve R = 51 gal/ft at 9 kn, V = 46,500 gal/min

If EPA continues to regulate ocean dumping by specifying an upper limit on the volume dumping rate, regardless of barge speed (so long as it exceeds 3 knots), the effective dumping rate should at least be considered when setting criteria for ocean dumping violations. For instances, Figure 3.3 illustrates the volume dumping rates and barge speeds for the barges surveyed during the September 1987 and 1988 surveys at the 106-Mile Site. Barges (events) DZ-1, DB-2, DB-3, DB-4, DB-21 and DB-23 were all dumping at rates below 15,500 gal/min, and at barge speeds greater than 3 kn, in accordance with permit requirements. Their effective dumping rates differed greatly, however, on account of large differences in barge speed. Event DB-3 had the lowest effective dumping rate ($R \approx 16$ gal/ft) because it had the highest barge speed; event DB-2 had the highest effective dumping rate ($R \approx 29$ gal/ft) of the four events, with volume dumping rates less than 15,500 gal/min. Nevertheless, the volume dumping rates for all of these barge events could have been increased substantially beyond 15,500 gal/min while maintaining an effective dumping rate less than 51 gal/ft (the EPA requirement based upon 15,500 gal/min and 3 kn).

Figure 3.3 also illustrates that although plume event DB-1 had a volume dumping rate in excess of 15,500 gal/min, its effective dumping rate ($R \approx 33$ gal/ft) was still less than the implied EPA rate of 51 gal/ft. These examples illustrate that, if sludge dumping rates are to be based upon water quality criteria, then dumping rates should be based upon the effective dumping rate; volume dumping rates could then be specified for a given barge speed, or range of speeds (e.g., 4-6 kn).

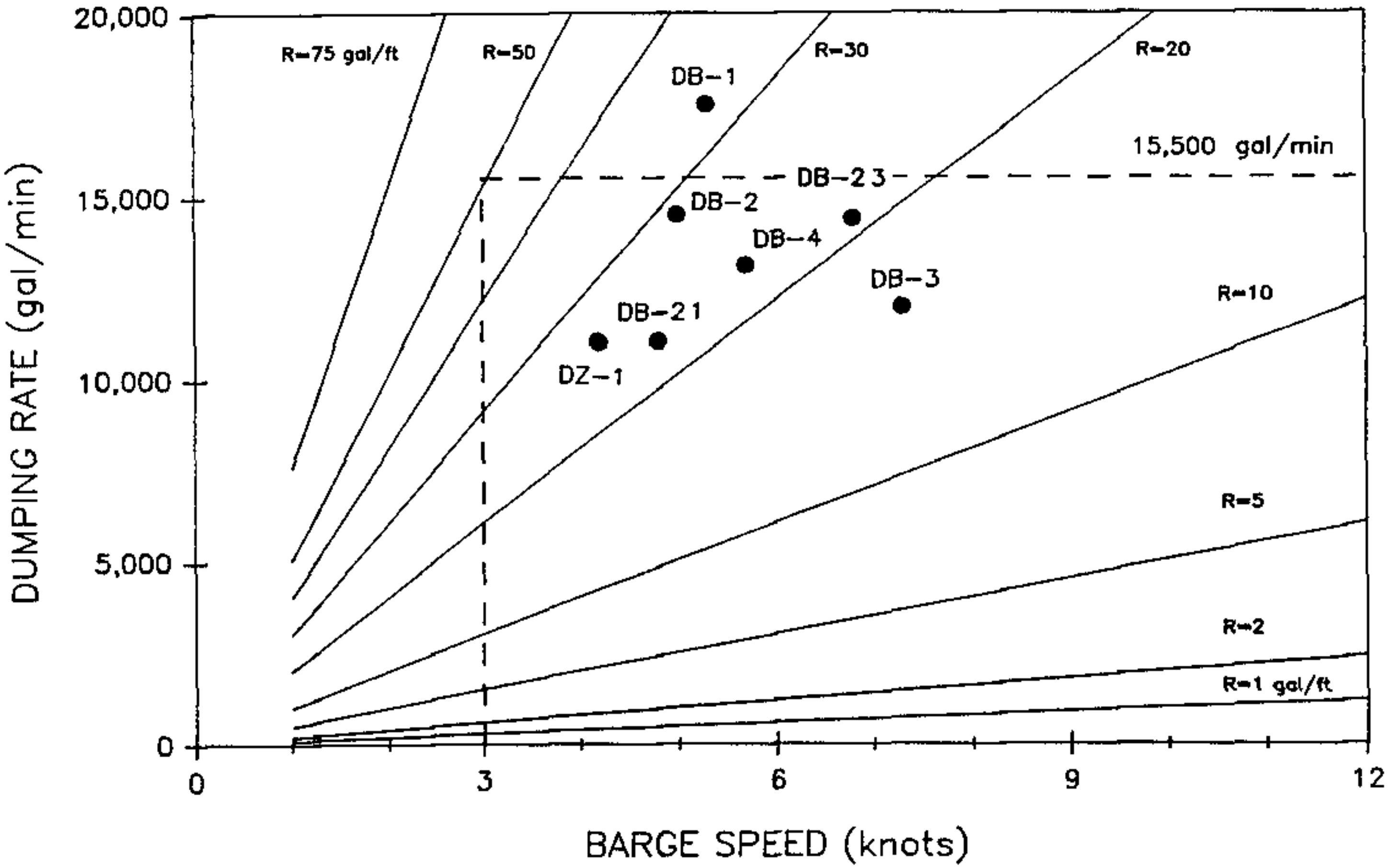

FIGURE 3.3 PLOT OF VOLUME DUMPING RATE (gal/min) VERSUS BARGE SPEED. VARIOUS CASES ARE GIVEN FOR THE EFFECTIVE DUMPING RATE, R, (gal/ft). BARGE DUMPING CHARACTERISTICS FROM SEPTEMBER 1987 AND 1988 ARE REPRESENTED BY INDIVIDUAL POINTS.

4. RECOMMENDED DUMPING RATES

The previous section presented an empirical equation (Eq. 8) for estimating the rate at which sewage sludge should be dumped in order to meet toxicity requirements and water quality criteria at the 106-Mile Site. Although additional field measurements will be necessary to validate this formula under a variety of oceanographic conditions, dumping rates, and barge configurations, EPA is currently faced with time constraints for sludge dumping permits, and consequently, this preliminary formula will be used to set initial sludge dumping rates for the 106-Mile Site. As additional field data become available from subsequent monitoring studies at the 106-Mile Site, modifications to the various coefficients in the dumping rate equation should be considered.

In the following subsections we use the empirical dumping rate equation to develop

- Specific dumping rates for each permit applicant.
- A nomograph for selection of dumping rates according to specific dilution requirements that may be specified at a later date.

4.1 DUMPING RATES FOR INDIVIDUAL PERMIT APPLICANTS

EPA Region II has received applications for permits to dump municipal sewage sludge at the 106-Mile Site from nine wastewater treatment authorities in New York and New Jersey:

Permit Applicants	Abbreviation
Passaic Valley Sewerage Commissioners	PVSC
Middlesex County Utilities Authority	MCUA
Bergen County Utilities Authority	BCUA
Linden-Roselle Sewerage Authority	LRSA
Rahway Valley Sewerage Authority	RVSA
Joint Meeting of Essex and Union Counties	JMEUC
New York City Department of Environmental Protection	NYCDEP
Nassau County Department of Public Works	NCDPW
Westchester County Department of Environment Facilities	WCDEF

Each permit application includes information on (1) the concentrations of chemical constituents within the whole sludge, and (2) results of whole sludge toxicity tests. With the exception of the NYCDEP, each permit application provides information on the sludge from a single treatment facility. In the case of NYCDEP, however, the permit application provides data on the maximum chemical concentration or most toxic toxicity test results obtained from any one of twelve treatment facilities. Thus, high chemical concentrations from a single New York City plant apply to all plants designated in the NYCDEP permit application.

Tables 4.1 and 4.2 present metal and toxicity characterization data, respectively, from analyses that were conducted on whole sludge samples obtained in August 1988 from the nine sewerage authorities in New York and New Jersey. Analytical methods and a comparison of results with data provided in the permit applications are provided in a separate report (Battelle, 1988f). The two tables also present estimates of the dilution that would be required to meet the applicable metal-based or toxicity-based water quality criteria.

As indicated in Table 4.1, the highest metal-based dilutions are governed by copper for eight of the nine sewerage authorities; mercury-based dilutions exceed those of copper only for the Bergen County Utilities Authority (BCUA). The metal-based dilutions range from 4,140 for Nassau County to 80,000 for BCUA. The toxicity-based dilutions also have a wide range of values: from 4,740 for Middlesex County to 166,700 for Linden-Roselle. Comparison of Tables 4.1 and 4.2 illustrates that metal-based dilutions exceed toxicity-based dilutions for five of the nine sewage authorities studied.

To relate the required dilutions presented in Tables 4.1 and 4.2 to actual sludge dumping rates, we have used the empirical dumping rate equation (Eq. 8) given in the previous section to calculate the volume dumping rate (in gal/min) that would be required to achieve the specified dilutions 4 h after dumping and thus meet water quality criteria.

Table 4.3 presents volume dumping rates for each sewerage authority based upon the required dilutions given in Tables 4.1 and 4.2; dumping rates are also given as a function of barge speed (e.g., 3, 6, and 9 kn). These

TABLE 4.1 WHOLE SLUDGE METAL CHARACTERIZATION RESULTS FROM THE NINE NEW YORK-NEW JERSEY SEWERAGE AUTHORITIES APPLYING FOR PERMITS TO DISCHARGE SEWAGE SLUDGE AT THE 106-MILE SITE. SAMPLES WERE COLLECTED IN AUGUST 1988.

	Metal (mg/L whole sludge)			
Authority	**Cu**	**Hg**	**Required Dilution[a]**	**Metal**
PVSC	42.0		14,500	Cu
MCUA	68.0		23,450	Cu
BCUA		2.00	80,000	Hg
LRSA	80.0		27,590	Cu
RVSA	16.0		5,520	Cu
JMEUC	36		12,410	Cu
NYCDEP	38.0		13,100	Cu
NCDPW	12.0		4,140	Cu
WCDEF	56.0		19,310	Cu

PVSC = Passaic Valley Sewerage Commissioners.
MCUA = Middlesex County Utilities Authority.
BCUA = Bergen County Utilities Authority.
LRSA = Linden-Roselle Sewerage Authority.
RVSA = Rahway Valley Sewerage Authority.
JMEUC = Joint Meeting of Essex and Union Counties.
NYCDEP = Composite of the New York City Department of Environmental Protection facilities.
NCDPW = Nassau County Department of Public Works.
WCDEF = Westchester County Department of Environmental Facilities.

[a]Dilution based on the metal requiring the greatest amount of dilution to meet water quality.

TABLE 4.2 WHOLE SLUDGE TOXICITY RESULTS FROM THE NINE NEW YORK-NEW JERSEY SEWERAGE AUTHORITIES APPLYING FOR PERMITS TO DISCHARGE SEWAGE SLUDGE AT THE 106-MILE SITE. SAMPLES WERE COLLECTED IN AUGUST 1988. THE MAXIMUM TOXICITY BASED SLUDGE DILUTION REQUIRED FOR EACH MUNICIPALITY ARE LISTED.

	LC50 (% whole sludge)		
Authority[a]	*Menidia beryllina*	*Mysidopsis bahia*	Toxicity Based Required Dilution[b]
PVSC	0.49	0.17	58,800
MCUA	5.95	2.11	4,740
BCUA	1.55	2.10	6,450
LRSA	0.53	0.06	166,700
RVSA	1.49	0.88	11,360
JMEUC	1.92	1.68	5,950
NYCDEP	1.59	2.25	6,290
NCDPW	2.33	0.92	10,870
WCDEFW	0.91	1.17	10,990

[a]Abbreviations are defined in Table 4.1.

[b]The species with the lowest LC50 and an application factor of 0.01 were used to determine the required dilution.

TABLE 4.3 COMPARISON OF SLUDGE DUMPING RATES BASED ON TOXICITY AND TRACE METAL RESULTS. REQUIRED DILUTION DATA WERE DERIVED FROM THE AUGUST 1988 SLUDGE CHARACTERIZATION STUDY. DUMPING RATES WERE BASED ON OBSERVED DILUTION RATES FROM THE SEPTEMBER 1988 SURVEY AT THE 106-MILE SITE.

Authority[a]	Required Dilution	Recommended Dumping Rate (gal/min) 3 kn	6 kn	9 kn
		Toxicity Basis		
PVSC	58,800	210	420	630
MCUA	4,740	4,359	8,719	13,078
BCUA	6,450	2,684	5,368	8,052
LRSA	166,700	85	171	256
RVSA	11,360	1,276	2,552	3,828
JMEUC	5,950	3,024	6,048	9,072
NYCDEP	6,290	2,784	5,568	8,352
NCDPW	10,870	1,347	2,694	4,041
WCDEF	10,990	1,329	2,658	3,987
		Metal Basis		
PVSC	14,500	955	1,911	2,866
MCUA	23,450	556	1,113	1,669
BCUA	80,000	153	306	459
LRSA	27,590	466	933	1,399
RVSA	5,520	3,393	6,786	10,179
JMEUC	12,410	1,147	2,295	3,442
NYCDEP	13,100	1,076	2,152	3,228
NCDPW	4,140	5,582	11,164	16,746
WCDEF	19,310	690	1,380	2,070

[a]Abbreviations are defined in Table 4.1.

results indicate that sludge dumping rates must be reduced greatly from the court-mandated rate of 15,500 gal/min in order that sludge concentrations 4 h after dumping are sufficiently low to meet EPA water quality criteria. At a barge speed of 6 kn, recommended dumping rates for the nine permit applicants vary from 171 to 8,719 gal/min based upon toxicity requirements; 306 to 11,164 gal/min based upon metals.

The recommended dumping rate for each permit applicant is, therefore, dependent upon the speed of the barge (Table 4.3). As demonstrated in Section 3, dilution requirements dictate an effective dumping rate, but volume dumping rates are based upon the effective dumping rate and the barge speed. Accordingly, volume dumping rates are directly proportional to barge speed, such that barges traveling at 3 kn must dump at one-half the rate of a barge with a speed of 6 kn, and one-third the rate of a barge with a speed of 9 kn. Thus, barges that travel relatively fast (7 to 9 kn) could dump at 2 to 3 times the dumping rate of slow (3 kn) barges, and meet water quality criteria. The effect of barge speed on dumping rate is, however, a lesser issue than the actual range of recommended dumping rates that are given in Table 4.3. A major reduction in dumping rates from 15,500 gal/min to near 1,000 gal/min would represent more than a 15-fold decrease in rates, and consequently, more than a 15-fold increase in the time for a barge to dump its load at the 106-Mile Site. The logistical repercussions of this long dumping time are discussed in Section 5.

4.2 NOMOGRAPH OF DUMPING RATES FOR SPECIFIC DILUTION REQUIREMENTS

The previous subsection presented specific dumping rates for each of the nine permit applicants. These rates were based upon whole sludge data that were determined from the characterization study conducted in August 1988 (EPA , 1992d). We anticipate that additional chemical constituent and toxicity data will be acquired over the next few years for the various sludges dumped at the 106-Mile Site, and for this reason, a simplified algorithm or nomograph will be needed to determine optimum dumping rates as a function of the required dilution. For this purpose, Figure 4.1 illustrates the relationship between the required dilution and the sludge dumping rate, expressed in units of gal/min. The data are presented on logarithmic scales

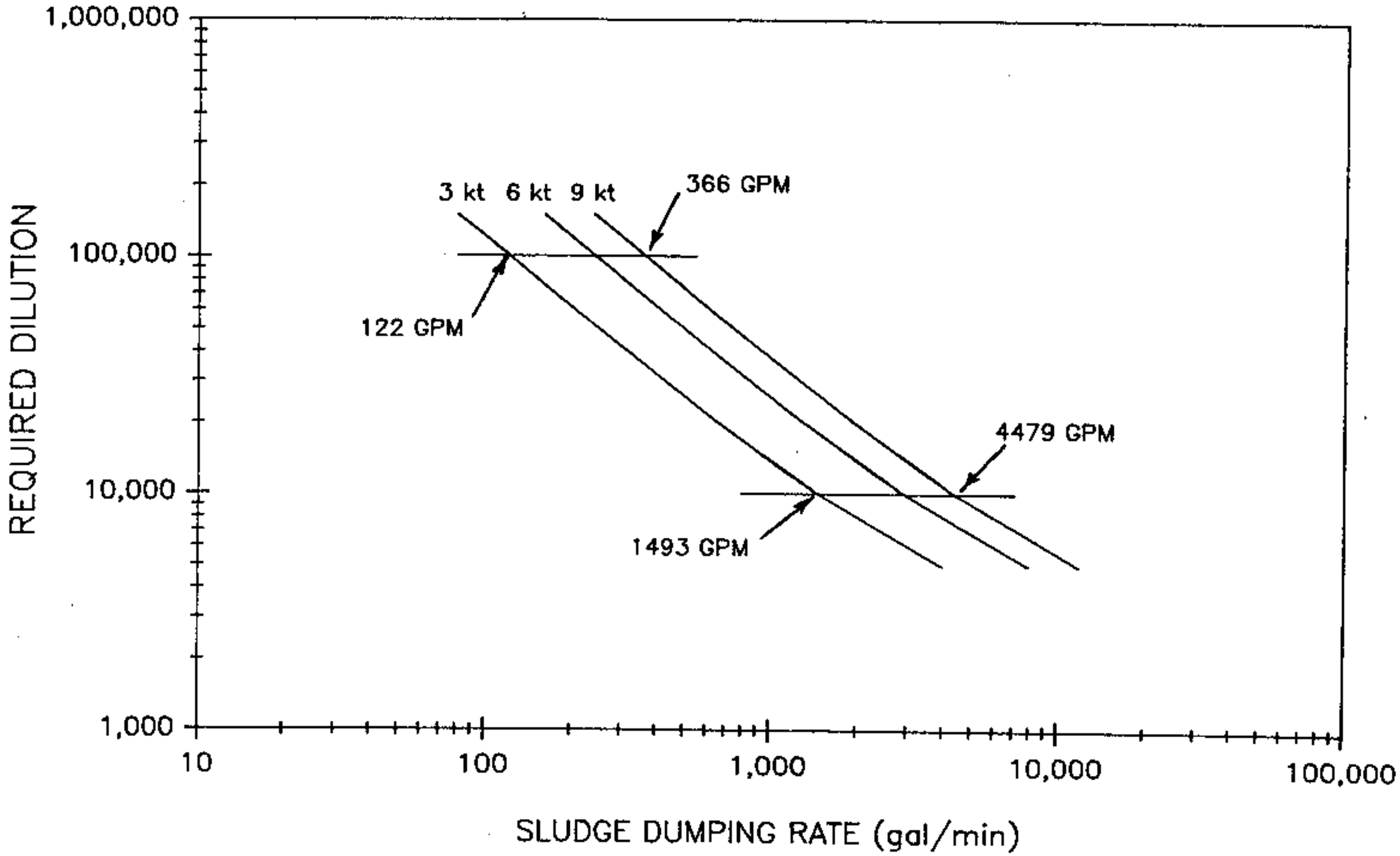

FIGURE 4.1 NOMOGRAPH OF SLUDGE DUMPING RATES (in gal/min) VERSUS REQUIRED SLUDGE DILUTIONS 4-h AFTER DUMPING AT THE 106-MILE SITE. SEPARATE CURVES ARE GIVEN FOR BARGE SPEEDS OF 3, 6, AND 9 kn. CALCULATIONS BASED UPON FIELD OBSERVATIONS OF SLUDGE DILUTION DURING SEPTEMBER 1988.

to accommodate the wide ranges of dilution and dumping rates that may be encountered. In accordance with Eq. (8), dumping rates are inversely proportional to required dilution, and increases in barge speed can effectively raise the permissible dumping rate for a given dilution requirement. Because it is difficult to extract values from this graphic presentation, the same data are presented in Table 4.4 for dilutions ranging from 5,000 to 150,000, and barge speeds of 3, 6 and 9 kn.

TABLE 4.4 RECOMMENDED SLUDGE DUMPING RATES VERSUS REQUIRED DILUTION. VOLUME DUMPING RATES (gal/min) ARE GIVEN FOR THREE BARGE SPEEDS.

Required Dilution	Effective Dumping Rate (gal/ft)	Barge Speed:	Volume Dumping Rate (gal/min) 3 kn	6 kn	9 kn
5,000	11.4		3,982	7,963	11,945
10,000	2.5		1,493	2,986	4,479
15,000	1.4		919	1,838	2,757
20,000	0.98		664	1,328	1,992
25,000	0.75		520	1,039	1,559
30,000	0.61		426	853	1,279
40,000	0.44		314	628	942
50,000	0.34		249	498	747
75,000	0.22		163	327	490
100,000	0.17		122	244	366
125,000	0.13		97	194	291
150,000	0.11		80	161	241

Note: The effective dumping rate (gal/ft) to achieve the required dilution is independent of barge speed.

5. STRATEGIES FOR MULTIPLE DUMPING

The previous sections addressed the initial (4-h) dilution of discrete parcels of sewage sludge dumped at the 106-Mile Site. Dilution calculations and, therefore, dumping rate formulas were based upon discrete parcels, rather than plume-average sludge concentrations, because the EPA regulations for ocean dumping of municipal wastes are directed at waste parcels rather than spatial averages of entire waste plumes. Consideration of dumping strategies and waste loading at the site does, however, require analyses of whole plumes and calculations on spatial scales that include the entire dumpsite.

In this section, we raise a number of practical issues and considerations concerning the present and future dumping of sludge at the 106-Mile Site. The following subsections address the topics listed below:

- Bulk loading of sludge at the 106-Mile Site
- Strategies for dumping at present rates of 15,500 gpm
- Considerations for dumping at greatly reduced rates.

5.1 BULK LOADING CONSIDERATIONS

The volume (load) of sludge dumped at the 106-Mile Site is estimated to be roughly 7.2 million wet metric tons (1.7 billion gallons) annually, or 20,000 m^3 per day (Walker et al., 1987). The magnitude of this dumping activity, coupled with the presumed ecological effects of sludge on the marine life of the U.S. east coast, has fueled great concern for sludge dumping at the 106-Mile Site. To determine the true fate and effects of sludge dumping at the 106-Mile Site will require an extensive monitoring activity as outlined in the 106-Mile Site monitoring plan (EPA , 1988a). This monitoring activity is under way, but information on the farfield fate and long-term effects of sludge dumping will not be available for another year or two.

Prior to implementation of the 106-Mile Site monitoring plan, Walker et al. (1987) developed a model of the farfield transport and fate of sewage sludge dumped at the 106-Mile Site. Their transport model was based upon (1) observations of mean southwestward currents at the site, and (2) estimates of sludge loading at the site, rates of turbulent mixing within the barge wake, and sludge diffusion rates over time scales of days to months. This model provides estimates of the mean transport of sludge-derived pollutants dumped at the 106-Mile Site. In addition, maps are provided to illustrate the two-dimensional distribution of sludge concentration (dilution) along the U.S. east coast. These steady-state model results, which were based upon a dumping rate of 20,000 m^3 of sludge per day, indicate that minimum dilutions (highest sludge concentrations) within 50 km of the site would be on the order of 1,000,000:1. Clearly, these dilutions are 2 or 3 orders of magnitude greater than the dilutions that were observed during the nearfield surveys of sludge plumes within the 106-Mile Site. Although the Walker et al. model may represent the farfield, long-term fate of sludge dumped at the 106-Mile Site, it does not represent actual nearfield dilutions.

As a first step toward analyses of sludge loading within the 106-Mile Site and on times scales of the dumping operations (hours to days), Table 5.1 presents basic calculations of the site receiving volume and the amount of sludge that is now being dumped at the site. If the depth of the receiving volume during summer is taken as the depth of the seasonal pycnocline (20 m), and the dimensions of the site are 7.2 km by 37.0 km, then the receiving volume in summer is approximately 10.7 x 10^9 m^3. Thus, one NYCDEP barge load of sludge (12,500 m^3) mixed evenly throughout the dumpsite in summer would result in an average sludge dilution of ≈426,000:1. Likewise, if 10 barges dumped sludge at the site during a week-long period without circulation (zero net current), the resulting site-averaged dilution would be ≈42,600:1 in summer. These dilution estimates will certainly vary with the number and size (sludge capacity) of the barges that would be dumping during a period of no circulation, but this simple calculation leads to the following conclusion:

- If no circulation were to persist for a week or so during summer months, and dumping activities consisted of at least 1 barge per day, then site-averaged sludge dilutions may be as low as 50,000:1. This condition represents the worst-case for sludge loading because these site-averaged dilutions are less than the minimum required dilutions for some of the sludges being dumped at the 106-Mile Site (see Tables 4.1 and 4.2).

The nearfield results from the winter 1988 survey at the 106-Mile Site (EPA , 1988a) indicated that, on time scales of less than one day, sludge may not settle in significant quantities beyond a depth of roughly 30 m. Although sludge may penetrate deeper during periods of active mixing (e.g., storm events), the data suggest that the depth of the permanent pycnocline (≈100 m) is an overestimate of the actual depth of the mixing (receiving) volume during the first few days following dumping. Therefore, on time scales of a few days, the receiving volume in winter may not be significantly greater than during summer (thus contrary to earlier theories based simply upon pycnocline depth).

We suspect that, due to significant currents that flush the site on times scales of 2 to 20 hours, site-averaged sludge loading at the 106-Mile Site is not a problem for most days of the year. Additional site-specific field data are needed for meaningful statistics on the frequency of week-long stagnant flow periods, but we estimate that such events would not occur more than one or two times during the 5-month "summer" season.

5.2 DUMPING STRATEGIES AT COURT-ORDERED RATE OF 15,500 gpm

The present court order for dumping of municipal sludge at the 106-Mile Site contains the following specifications:

- Dumping rates must not exceed 15,500 gpm.
- Barges must maintain speeds of at least 3 kn.
- Sludge must be dumped within the 106-Mile Site boundaries.
- An individual plume must not cross nor come within 1/2 mile of itself at any point.

Modifications to the dumping rates are being considered (e.g., this report), and the effects of barge speed on sludge dilution may also be the topic of future studies related to ocean dumping. One of the most basic questions, "Along what track should sludge be dumped within the site?", has, however, received little attention compared with other issues. In this subsection we propose a few strategies that may help to ensure that sludge dumping at the 106-Mile Site will meet EPA water quality criteria.

In Section 3, an empirical equation (Eq. 8) was developed for prediction of sludge dumping rates that will ensure that water quality criteria are met 4 h after dumping. If, however, sludge plumes cross the site boundaries in less than 4 h, dilutions will be less than those predicted at 4 h and, therefore, the dumping rates will be too high. Therefore, if the dumping rates derived from Eq. (8) are to be used, then (1) plumes must not cross the site boundaries within 4 h after dumping, and (2) a plume must not cross another plume nor overlap itself within 4 h after dumping.

Ensuring that sludge plumes remain within the site for at least 4 h is a difficult task, considering that near-surface currents often attain speeds of 1 kn or more during periods when eddies pass through the site. Present dumping regulations permit dumping anywhere within the site or along its boundaries, and consequently, sludge may be transported out of the site within minutes or a few hours after dumping, depending upon the position of dumping and the direction and speed of the currents.

Below, we present candidate strategies for sludge dumping during three hypothetical flow regimes: weak flow, having current speeds <0.25 kn; moderate flow, with speeds between 0.25 and 1.5 kn; and strong flow, with speeds >1.5 kn. In reality, this range of current speeds can be obtained from all current directions, but we have based the present analyses upon the worst-case flow condition: east-west flow, directed across the narrow (4.5 nmi; 7.4 km) width of the dumpsite.

<u>Weak Flow (<0.25 kn)</u>

- Dumping must be prohibited within 1 nmi of all site boundaries to ensure that sludge does not cross site boundaries before 4 h after dumping.
- The track of a barge must not cross the track of a previous barge within the site unless at least 4 h has elapsed between the two dumping operations. If the start of dumping for individual barges could be separated by 4 h, then barges could follow the same track within the site.
- If simultaneous dumping is permitted, then dumping should be conducted along parallel, north-south lanes to ensure that plumes do not cross within 4 h after dumping. Three lanes could be

established: one along the center of the site (along 72°02.5'W); and two situated 1 nmi from both the east and west boundaries of the site (along 72°01'W and 72°04'W).

Moderate Flow (0.25 to 1.5 kn)

- If flow is easterly or westerly, then dumping must be directed along a north-south track that coincides with the site boundary on the upstream side of the site (e.g., east boundary for westward flow). This will ensure that plumes do not leave the site within 4 h of dumping.
- If flow is northerly or southerly, then dumping should be confined to the upstream half of the site (e.g., south of 38°50'N for northerly flow) to ensure that plumes do not leave the site within 4 h of dumping.
- If a single dumping track is established for periods of moderate flow, then dumping operations must be separated by at least 4 h.

Strong Flow (>1.5 kn)

- During periods of strong east-west flow, dumping should be prohibited because sludge plumes will cross the site boundaries in less than 3 h no matter where the material is originally dumped.
- During periods of strong north-south flow, dumping is permissible but all dumping should be confined to the upstream half of the site (e.g., south of 38°50'N for northerly flow) to ensure that plumes do not leave the site within 4 h of dumping.

The dumping strategies presented above would ensure proper management of sludge dumping operations at the 106-Mile Site, but they will require (1) near-real-time knowledge of surface currents at the site, and (2) close coordination between EPA and the transport companies that tow sludge barges to the 106-Mile Site. EPA currently plans to deploy a surface current mooring at the site in January 1989 for telemetry of near-real-time current data to EPA Region II. This mooring will provide continuous information on the speed and direction of the currents, which can be used to determine the optimum dumping strategy (see weak, moderate, or strong flow strategies given above). EPA could then post a radio bulletin, via the U.S. Coast Guard, that directs the transporters to dump according to a precoded strategy or lane designation.

It is important to note that failure to implement a dumping strategy such as that given above will definitely result in sludge plumes crossing the boundaries of the site within 4 h of a dumping operation.

The above strategies are well suited for dumping operations at roughly 15,500 gal/min and for all barges except the Seatrader I. To dump its load of roughly 9 million gallons of sludge, the Seatrader I requires about 12 h, and an in-site trackline of ≈50 nmi at a towing speed of 4 kn. A special dumping plan would be required for this exceptionally large barge.

5.3 DUMPING STRATEGIES AT REDUCED RATES

The previous subsection presented candidate dumping strategies that would be appropriate for sludge dumping rates of roughly 15,500 gpm (e.g., present rates). At this dumping rate, the New York barges take roughly 4 to 5 h to dump their entire load of 3.3 million gallons of sludge. At towing speeds of 5 kn, sludge plumes of New York barges are roughly the length of the dumpsite (20 nmi from 38°40'N to 39°00'N). Only the Seatrader I generates a plume that is 2 to 3 times the north-south length of the site.

From an operational standpoint, major problems arise if dumping rates are reduced by factors of 15 or more, as discussed in Section 4. For instance, if a New York barge were to dump at 1,000 gal/min, it would require about 60 h to dump its entire load. If the Seatrader I were to dump at 1,000 gal/min, it would require 6 days to dump its load of 9 million gallons. These long dumping times are a problem for several reasons:

- Transport costs for each barge load would be extremely high due to the extensive time away from port.
- The contracted tugs may not have the fuel or water capacity to remain at sea for periods of weeks.
- If the barges had to remain at the dumpsite for long periods, then additional barges (maybe 10 times as many as currently used) would be required by the New York and New Jersey sewerage authorities to dump the amount of sludge generated.
- Low dumping rates would result in vessel traffic problems within the site because 10 or more barges would be dumping simultaneously; this number of vessels steaming inside the relatively small dumpsite would be represent a navigational safety problem.

The issues presented above illustrate that sludge dumping at significantly reduced rates (say, 1,000 gal/min) may be environmentally acceptable, but they could be operationally unfeasible for the 106-Mile Site.

6. SUMMARY AND RECOMMENDATIONS

This report briefly reviews our knowledge of the nearfield, short-term behavior of plumes of sewage sludge dumped at the 106-Mile Site. Field observations of plume behavior and dilution during EPA surveys to the 106-Mile Site in September 1987 and 1988 have been used to develop an empirical equation for predicting the optimum rates of sludge dumping that satisfy EPA water quality criteria. Although data from a single plume event have been used to develop the dumping rate formula, the observed conditions and plume behavior may represent worst-case conditions for plume dilution (minimum dilution due to weak mixing conditions during a summer period with a shallow seasonal pycnocline). As data become available from additional nearfield monitoring surveys, the coefficients in the proposed dumping rate equation can be modified.

From the limited amount of plume observations acquired during the recent monitoring surveys, we can predict the following nearfield behavior of sludge dumped at the 106-Mile Site:

- During summer, sludge is primarily confined to the surface mixed layer (upper 20 m) above the seasonal pycnocline during the first 4 h after dumping.
- Parcels of concentrated sludge within the center of a plume are diluted at much slower rates than the average dilution for the entire plume.
- The rate of sludge dilution during the first 5 min after dumping within the barge wake is much greater than the rate of dilution from oceanographic mixing processes after wake mixing has ceased.
- Sludge dilutions 4 h after dumping may be as low as 5000:1 for individual sludge parcels; plume-averaged dilutions at 4 h may be 100,000:1 or greater.
- Plume break-up, which initiates rapid dilution of parcels, can occur before or after 4 h depending upon initial plume concentrations and oceanographic mixing conditions.

The results of this preliminary assessment of sludge plume behavior indicate that sludge dumping rates of 15,500 gal/min are too high to achieve the 4 h dilutions necessary to meet water quality criteria. Dumping rates should be less than 15,500 gal/min for all the permit applicants, based upon (1) sludge characteristics data and (2) observed mixing conditions at the 106-Mile Site. The results have also left a number of unanswered questions that require further considerations before we fully understand the nearfield fate of sludge dumped at the 106-Mile Site:

- How does the rate of sludge dilution vary with oceanographic mixing conditions, pycnocline depth, initial plume concentrations (dumping rate), and sludge characteristics? Were the environmental conditions encountered during the September 1987 and 1988 surveys representative for the site?

- Is wake-induced dilution a linear function of the effective dumping rate (the amount of sludge dumped per unit track length)?

- Do the sludge concentrations of parcels within plumes 4 h after dumping have a Gaussian distribution such that statistical techniques can be used to estimate the percentage of a plume that may violate water quality criteria?

- Can plume break-up be achieved earlier such that the rate of sludge dilution is increased? If, after initial wake-induced mixing, a plume is broader and/or more dilute, oceanic turbulent mixing will disperse the concentrate parcels of sludge more quickly.

- Do barge configurations and discharge methods have a significant effect on initial dilution?

- Are instantaneous dumping rates roughly equivalent to average dumping rates over the length of the plume? If not, water quality criteria may be greatly exceeded along portions of the plume.

- Does sludge settling and/or flocculation within the barge during transit create significant variations in sludge characteristics between the top and bottom of the sludge compartments? If so, large variations in sludge characteristics along the plume would result.

These questions lead to recommendations for additional analyses of existing data and additional measurements during future surveys to the 106-Mile Site:

- A statistically valid study of toxicity tests and laboratory analyses of chemical constituent concentrations should be conducted on sludge samples from each of the sewage treatment facilities to determine whether data from the permit applications and/or Santoro and Fikslin (1987) are representative of mean sludge characteristics and ranges of variability.

- Additional plume monitoring surveys should be conducted behind barges dumping at 15,500 gal/min to develop statistically defensible estimates of the rates of sludge dilution during the first 4 h after dumping. The effects of barge configuration, dumping rate, sludge characteristics, pycnocline depth, and oceanographic mixing conditions have yet to be quantified.

- If EPA is considering reductions in sludge dumping rates to ensure compliance with water quality criteria, then nearfield plume monitoring studies should be conducted behind barges dumping at reduced rated (e.g., 5,000 and 1,000 gal/min). Analyses will indicate whether rates of plume dilution are highly dependent upon dumping rates, such that 4-h dilutions, and hence permissible dumping rates, may be higher than those predicted from nearfield studies at dumping rates of 15,500 gal/min.

- Pretreatment of sludge and modifications to barge dumping procedures should be considered as alternatives to major reductions in dumping rates, especially as greatly reduced dumping rates would pose major operational problems to barge operators and permit applicants.

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